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Advanced Traffic Management on Arterial Corridors with Connected and Automated Vehicles

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Outline:

- arterial traffic measurement (for energy and emissions estimation)
- connected vehicles
- USDOT AERIS program efforts
- role of automation on arterial roadways

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UCR's Bourns College of Engineering Center for Environmental Research and Technology Transportation Systems Research Group

Research Areas of Interest:

- **Environmental and Mobility Impacts of Intelligent Transportation Systems**
- **Applications of Integrated Transportation / Emissions Modeling: current (freight) and future applications (connected and automated vehicles)**
- **Innovative Navigation Systems, Mapping & Positioning, Digital Infrastructure**

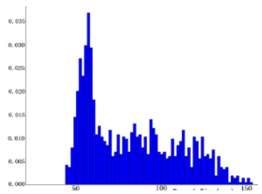
Traffic Activity

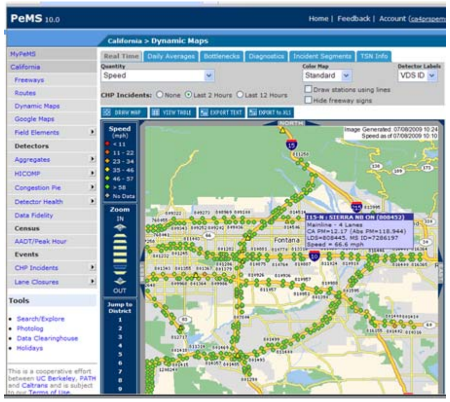
Freeway Traffic (uninterrupted flow)

Speed (mph)
Flow (veh/hr)
Density (veh/mile)

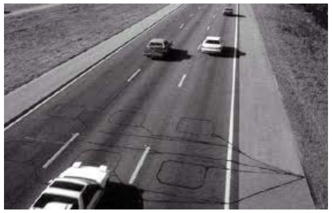
Arterial Traffic (interrupted flow)

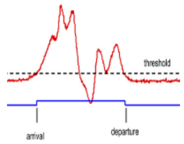
(Link) Travel Time Distribution





PeMS
(Inductive loop detector)





Fixed-location Sensors (re-identification)

Sparse Mobile Data

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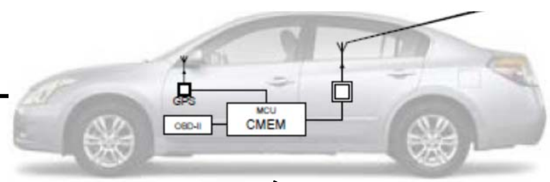
Energy/Emissions

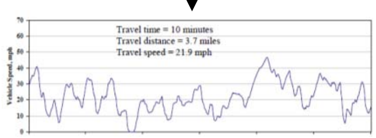
Microscopic

Portable Emission Measurement System

- High variability
- Take space in trunk

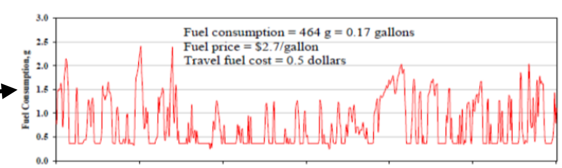
OBD-II





Vehicle activity
(e.g. speed trajectory)

Microscale Emissions Model (e.g. CMEM)



Energy/Emission

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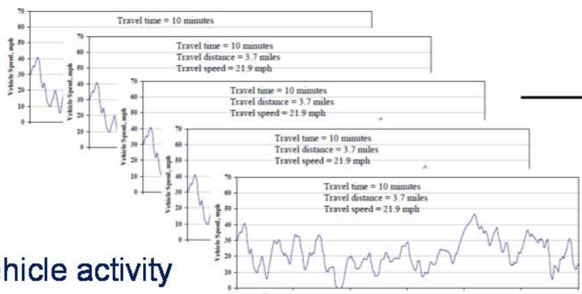
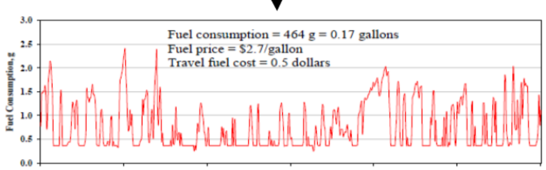
Energy/Emissions

Microscopic | **Mesoscopic** | **Macroscopic**



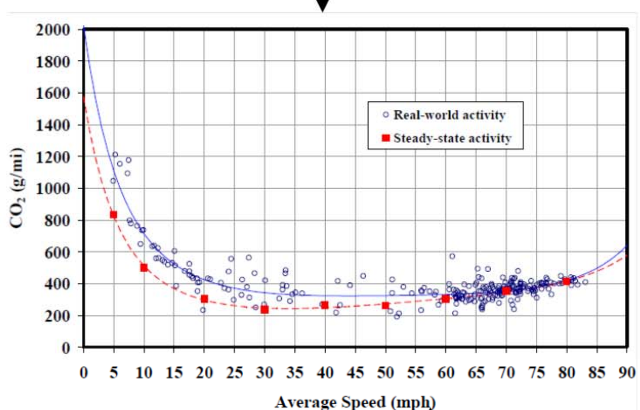
Vehicle activity
(e.g. speed trajectory)

Microscale Emissions Model (e.g. CMEM)



Energy/Emission

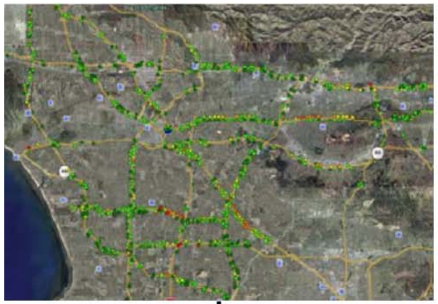
Off-line



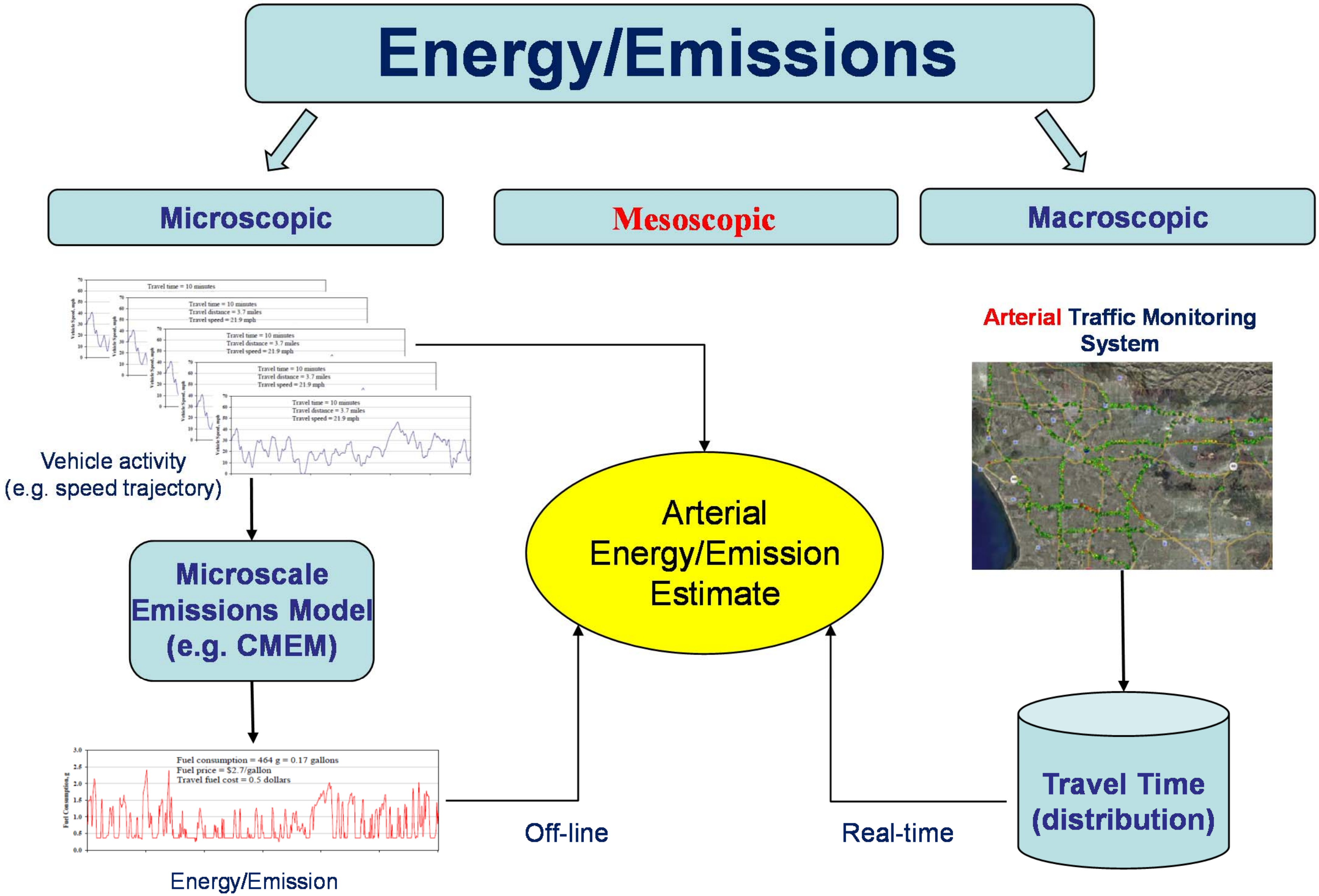
Off-line

Real-time

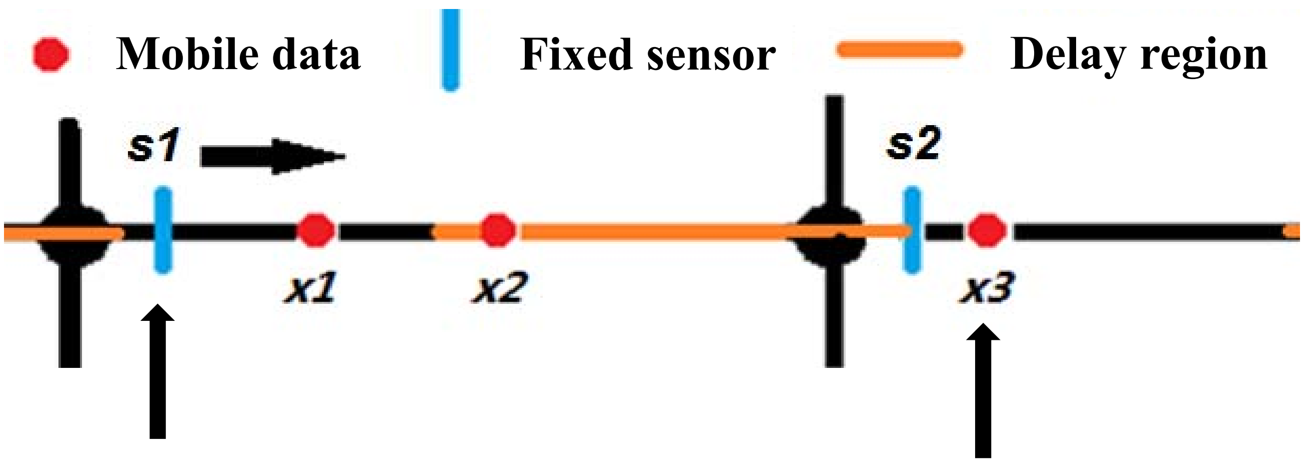
Traffic Monitoring System

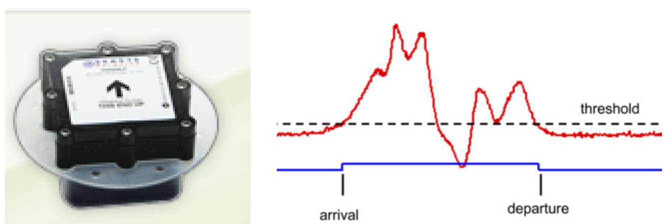


Traffic Activity (average speed)


Energy/Emissions
Microscopic
Mesoscopic
Macroscopic
Travel time = 10 minutes
Travel distance = 3.7 miles
Travel speed = 21.9 mph
Vehicle activity
(e.g. speed trajectory)
Microscale Emissions Model (e.g. CMEM)
Fuel consumption = 464 g = 0.17 gallons
Fuel price = $2.7/gallon
Travel fuel cost = 0.5 dollars
Energy/Emission
Arterial Energy/Emission Estimate
Off-line
Real-time
Arterial Traffic Monitoring System
Travel Time (distribution)

Travel Time Measurement





After vehicle re-identification

$TT_{s_1 s_2}, D_{fixed}$

Sparse data

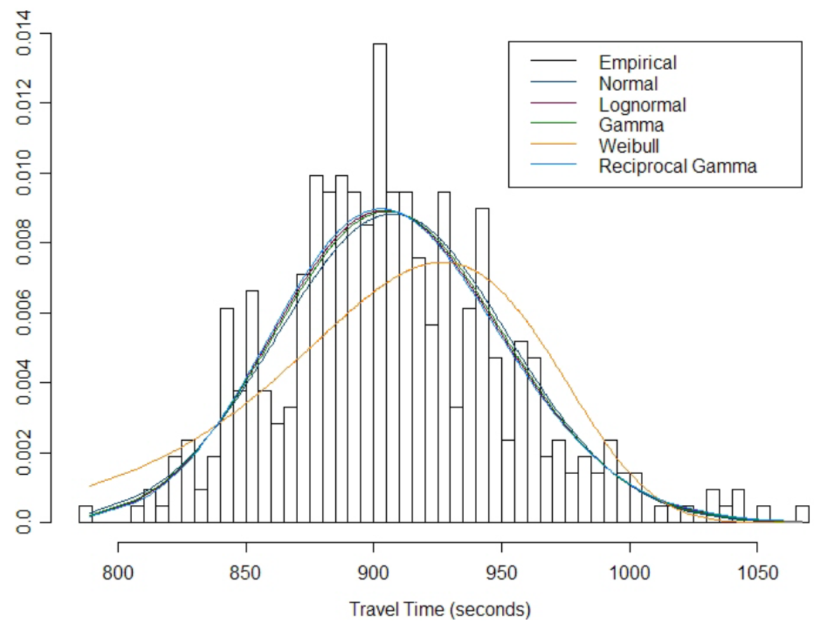
$t_{x_1}, t_{x_3}, (lat, lon)_{x_1}, (lat, lon)_{x_3}$

After map matching

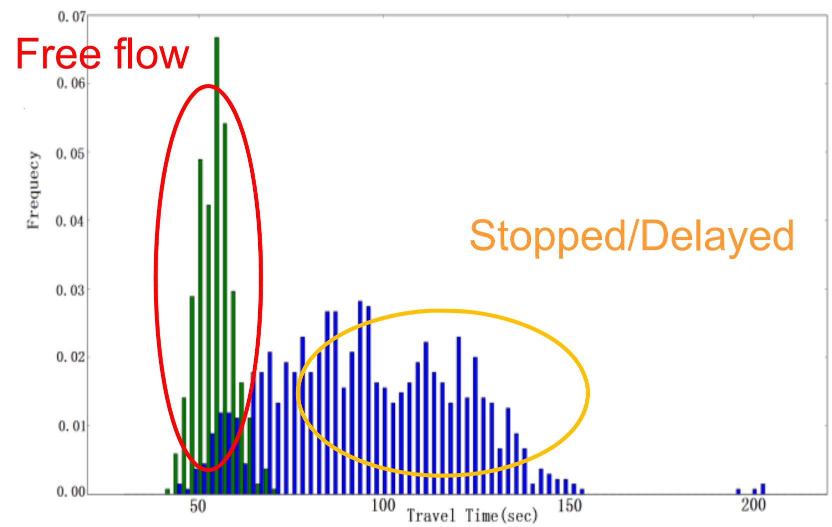
$TT_{x_1 x_3}, \ Dist_{x_1 x_3}$

Travel Time Distribution (TTD)

Freeway (Single-Mode)



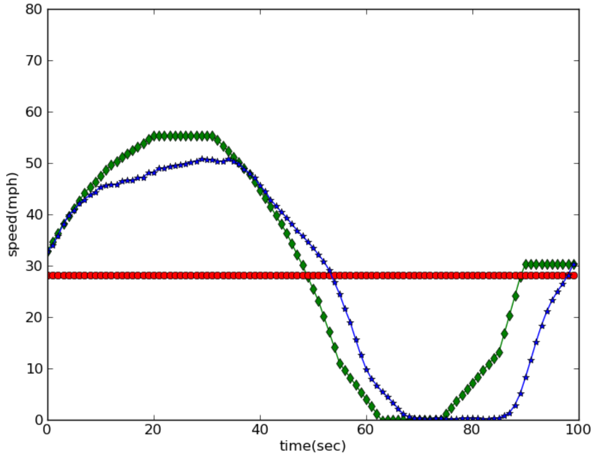
Arterial (Multi-Mode)
(Free flow travel time + Delay time)

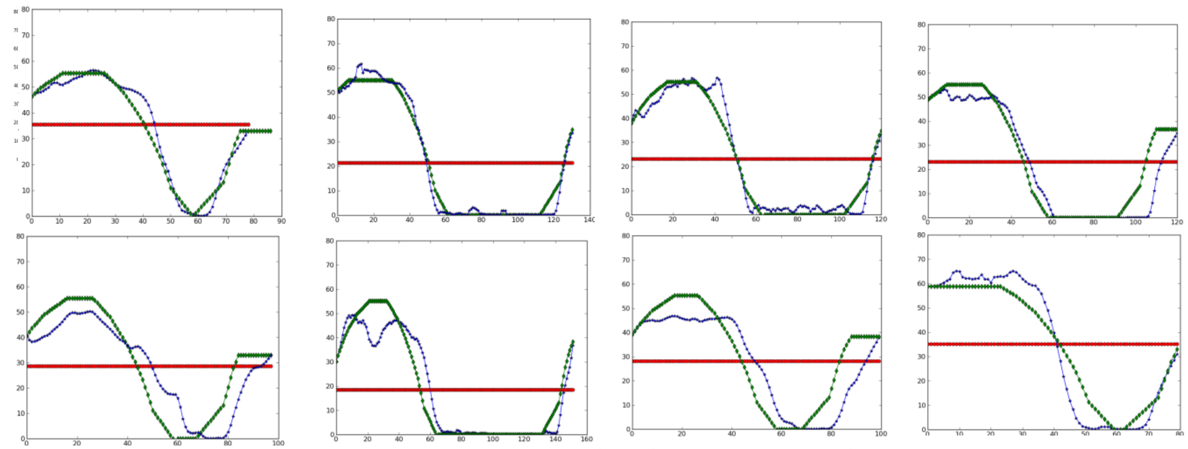


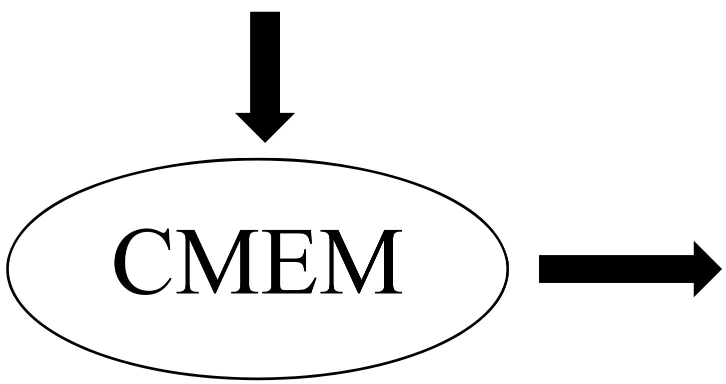
Solution: Modified Gaussian Mixture Model to obtain distributions

(see Q. Yang, G. Wu, K. Boriboonsomsin, M. Barth, "Arterial Roadway Travel Time Distribution Estimation and Vehicle Movement Classification using a Modified Gaussian Mixture Model", *Proceedings of the IEEE 2013 Intelligent Transportation Systems Conference*, The Hague, Netherlands, October 2013, pp. 681-686.

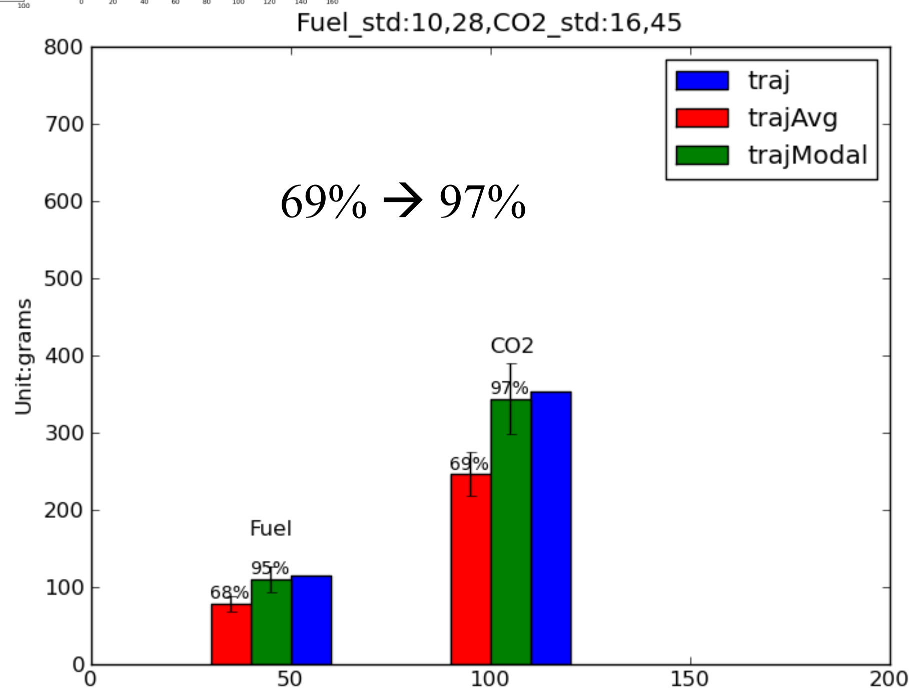
Example Results: Emission and Fuel Consumption Evaluation (56 stop probe trajectories from intersection 6 at Telegraph Rd, Chula Vista)







vehicle type: sedan



Connected Vehicles: providing better interaction between vehicles and between vehicles and infrastructure

- increased Safety
- better Mobility
- lower Environment impact

Connected Vehicle Applications (Phase 1)

V2I Safety

- Red Light Violation Warning
- Curve Speed Warning
- Stop Sign Gap Assist
- Spot Weather Impact Warning
- Reduced Speed/Work Zone Warning
- Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Blind Spot/Lane Change Warning (BSW/LCW)
- Do Not Pass Warning (DNPW)
- Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

- Probe-based Pavement Maintenance
- Probe-enabled Traffic Monitoring
- Vehicle Classification-based Traffic Studies
- CV-enabled Turning Movement & Intersection Analysis
- CV-enabled Origin-Destination Studies
- Work Zone Traveler Information

Environment

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Wireless Inductive/Resonance Charging
- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Eco-Traveler Information
- Eco-Ramp Metering
- Low Emissions Zone Management
- AFV Charging / Fueling Information
- Eco-Smart Parking
- Dynamic Eco-Routing (light vehicle, transit, freight)
- Eco-ICM Decision Support System

Road Weather

- Motorist Advisories and Warnings (MAW)
- Enhanced MDSS
- Vehicle Data Translator (VDT)
- Weather Response Traffic Information (WxTINFO)

Mobility

- Advanced Traveler Information System
- Intelligent Traffic Signal System (I-SIG)
- Signal Priority (transit, freight)
- Mobile Accessible Pedestrian Signal System (PED-SIG)
- Emergency Vehicle Preemption (PREEMPT)
- Dynamic Speed Harmonization (SPD-HARM)
- Queue Warning (Q-WARN)
- Cooperative Adaptive Cruise Control (CACC)
- Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
- Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
- Emergency Communications and Evacuation (EVAC)
- Connection Protection (T-CONNECT)
- Dynamic Transit Operations (T-DISP)
- Dynamic Ridesharing (D-RIDE)
- Freight-Specific Dynamic Travel Planning and Performance
- Drayage Optimization

Smart Roadside

- Wireless Inspection
- Smart Truck Parking

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USDOT AERIS Program:

CV Applications for the Environment: Real-Time Information Synthesis

Vision – Cleaner Air Through Smarter Transportation

- Encourage the development and deployment of technologies and applications that **support a more sustainable relationship between surface transportation and the environment** through fuel-use reductions and more efficient use of transportation services.

Objectives – Investigate whether it is possible and feasible to:

- **Identify connected vehicle applications** that could provide environmental impact reduction benefits via reduced fuel use, improved vehicle efficiency, and reduced emissions.
- **Facilitate and incentivize "green choices" by transportation service consumers** (i.e., system users, system operators, policy decision makers, etc.).
- **Identify vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-grid (V2G) data (and other) exchanges** via wireless technologies of various types.
- **Model and analyze connected vehicle applications** to estimate the potential environmental impact reduction benefits.
- **Develop a prototype** for one of the applications to test its efficacy and usefulness.

AERIS OPERATIONAL SCENARIOS & APPLICATIONS

ECO-SIGNAL OPERATIONS

- **Eco-Approach and Departure at Signalized Intersections** *(similar to SPaT)*
- **Eco-Traffic Signal Timing** *(similar to adaptive traffic signal systems)*
- **Eco-Traffic Signal Priority** *(similar to traffic signal priority)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Wireless Inductive/Resonance Charging**

ECO-LANES

- **Eco-Lanes Management** ***(similar to HOV Lanes)***
- **Eco-Speed Harmonization** ***(similar to variable speed limits)***
- **Eco-Cooperative Adaptive Cruise Control** *(similar to adaptive cruise control)*
- **Eco-Ramp Metering** *(similar to ramp metering)*
- **Connected Eco-Driving** *(similar to eco-driving)*
- **Wireless Inductive/Resonance Charging**
- **Eco-Traveler Information Applications** *(similar to ATIS)*

LOW EMISSIONS ZONES

- **Low Emissions Zone Management** *(similar to Low Emissions Zones)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Eco-Traveler Information Applications** *(similar to ATIS)*

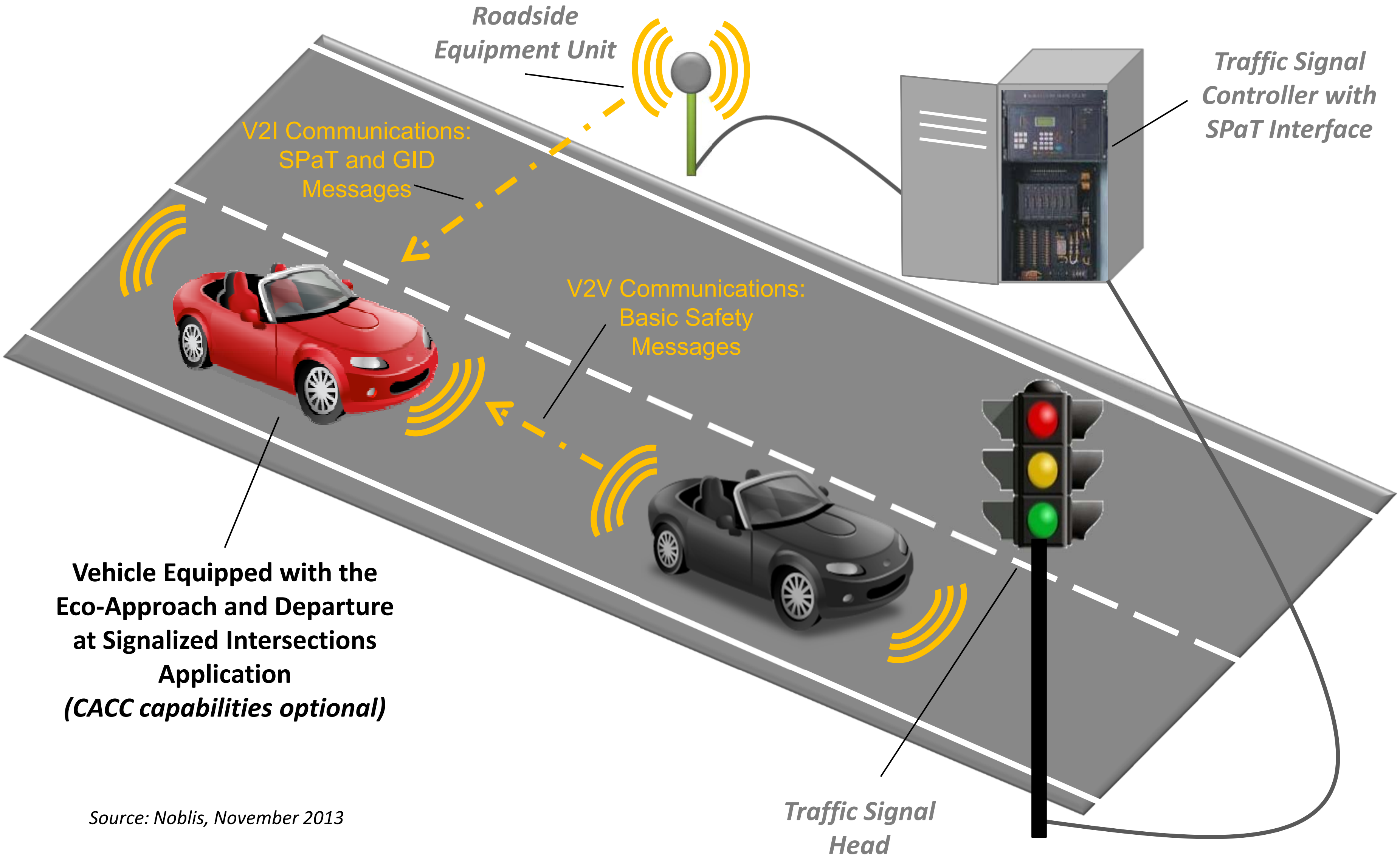
ECO-TRAVELER INFORMATION

- **AFV Charging/Fueling Information** *(similar to navigation systems providing information on gas station locations)*
- **Eco-Smart Parking** *(similar to parking applications)*
- **Dynamic Eco-Routing** *(similar to navigation systems)*
- **Dynamic Eco-Transit Routing** *(similar to AVL routing)*
- **Dynamic Eco-Freight Routing** *(similar to AVL routing)*
- **Multi-Modal Traveler Information** *(similar to ATIS)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*

ECO-INTEGRATED CORRIDOR MANAGEMENT

- **Eco-ICM Decision Support System** *(similar to ICM)*
- **Eco-Signal Operations Applications**
- **Eco-Lanes Applications**
- **Low Emissions Zone s Applications**
- **Eco-Traveler Information Applications**
- **Incident Management Applications**

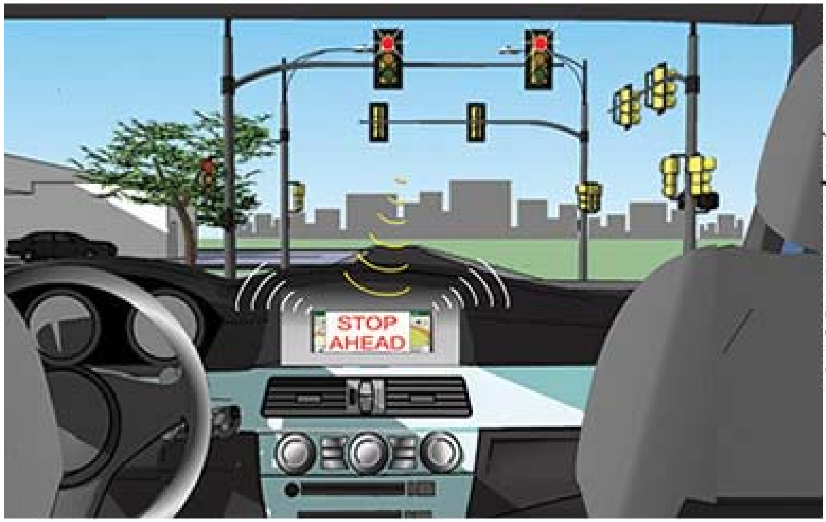
Eco-Approach and Departure at Signalized Intersections



Source: Noblis, November 2013

Signal Phase and Timing (SPaT)

- Data are broadcast from traffic signal controller (infrastructure) to vehicles (I2V communications)
- SPaT information consists of intersection map, phase and timing (10 Hz), and localized GPS corrections
- Can be broadcast locally via Dedicated Short Range Communication (DSRC) or cellular communications



Dan Morin, Volpe Center/USDOT

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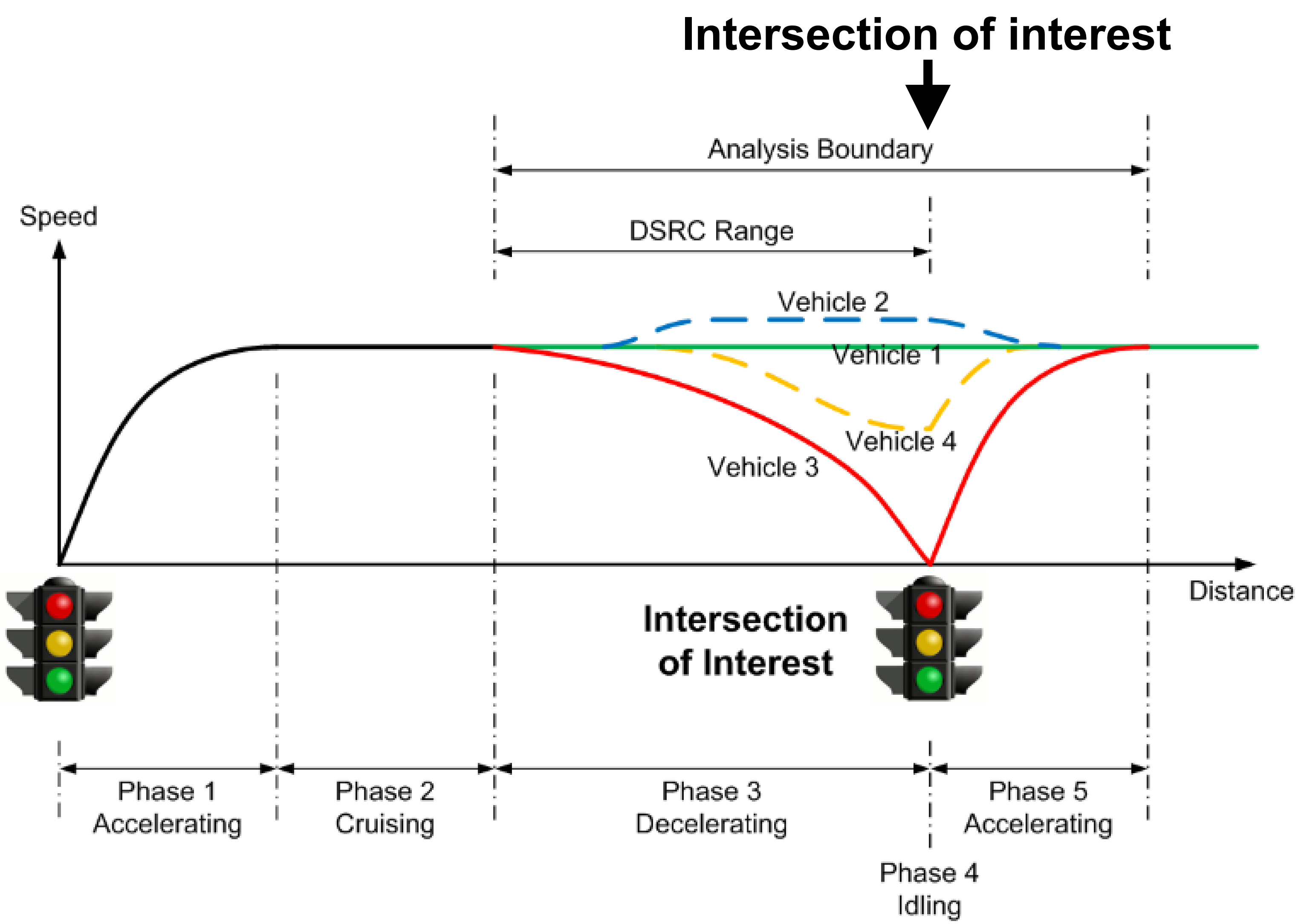
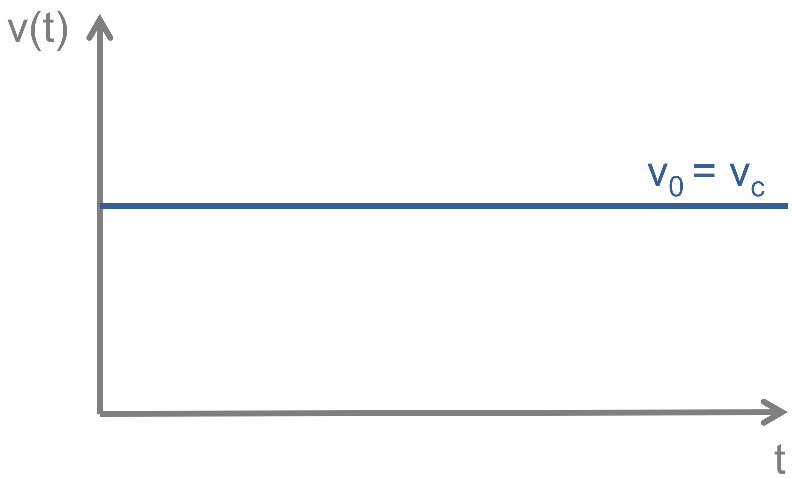
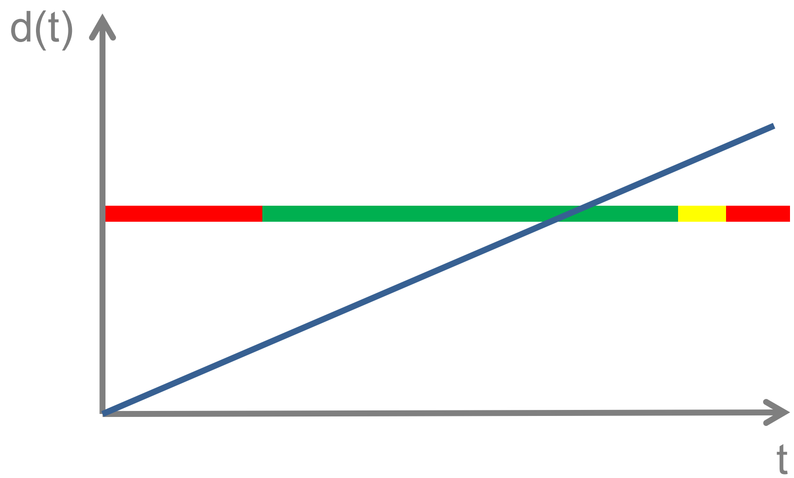
Eco-Approach and Departure Scenario Diagram



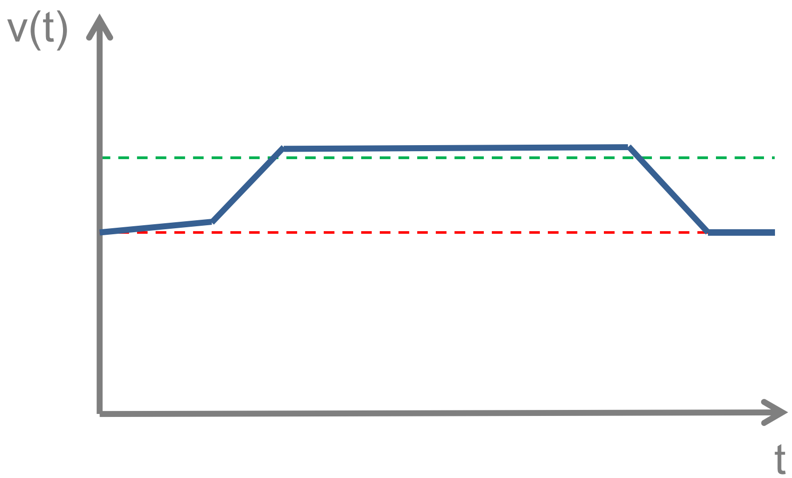
Scenario 1: Maintain speed to pass through green

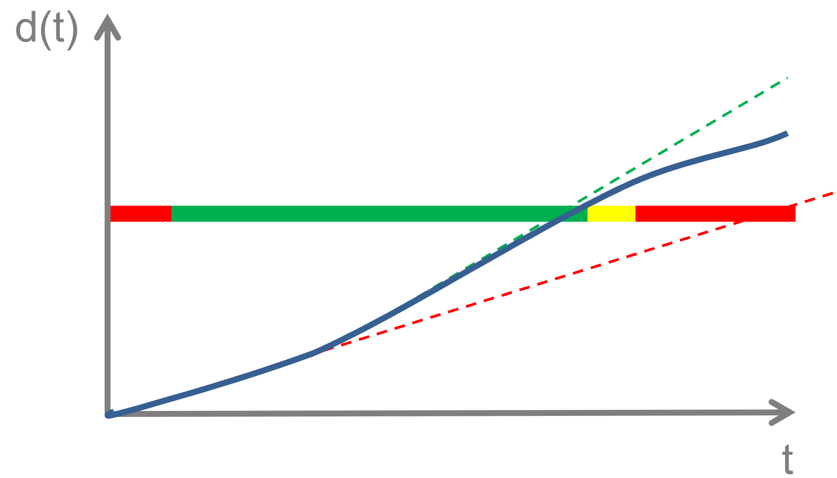




- **The vehicle passes through the intersection on the green phase without having to slow down or speed up**
- **Environmental benefits result from maintaining speed and reducing unnecessary accelerations**

Scenario 2: Speed Up to pass through green





- **The vehicle needs to safely speed up to pass through the intersection on a green phase**
- **Energy savings result from the vehicle avoiding a stop and idling at the intersection**

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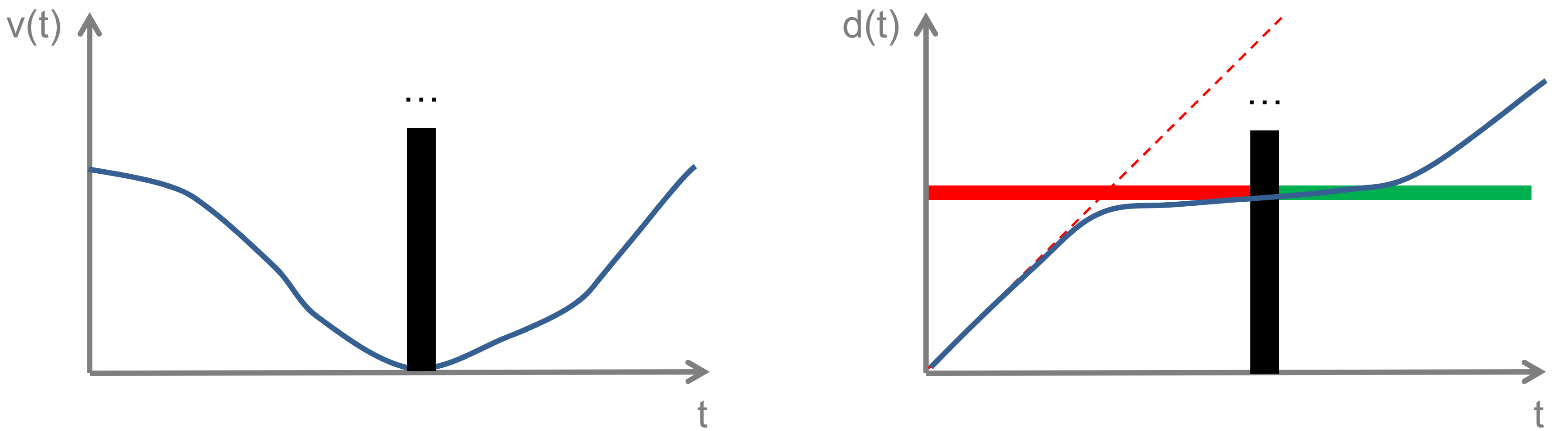
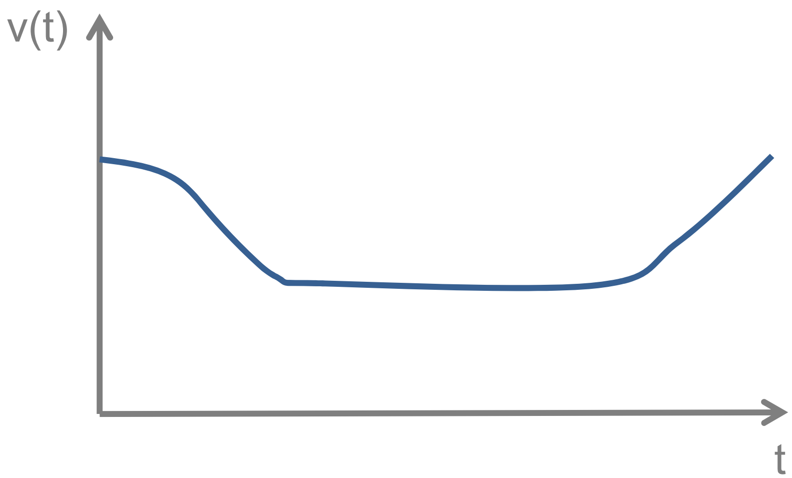
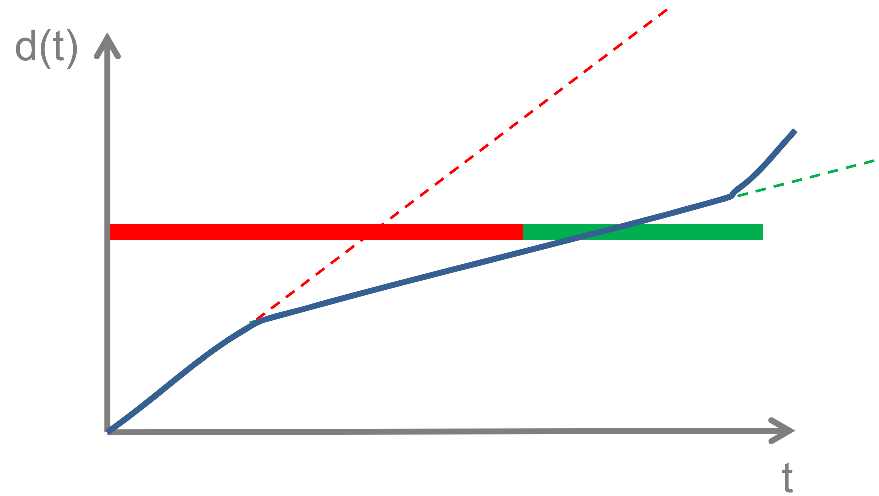
Scenario 3: Coast to stop at Intersection



- **The vehicle cannot make the green light and needs to slow down to stop at the signalized intersection**
- **Energy savings result from slowing down sooner and coasting to the stop bar**
- **Once stopped, the vehicle could engage engine start-stop capabilities**

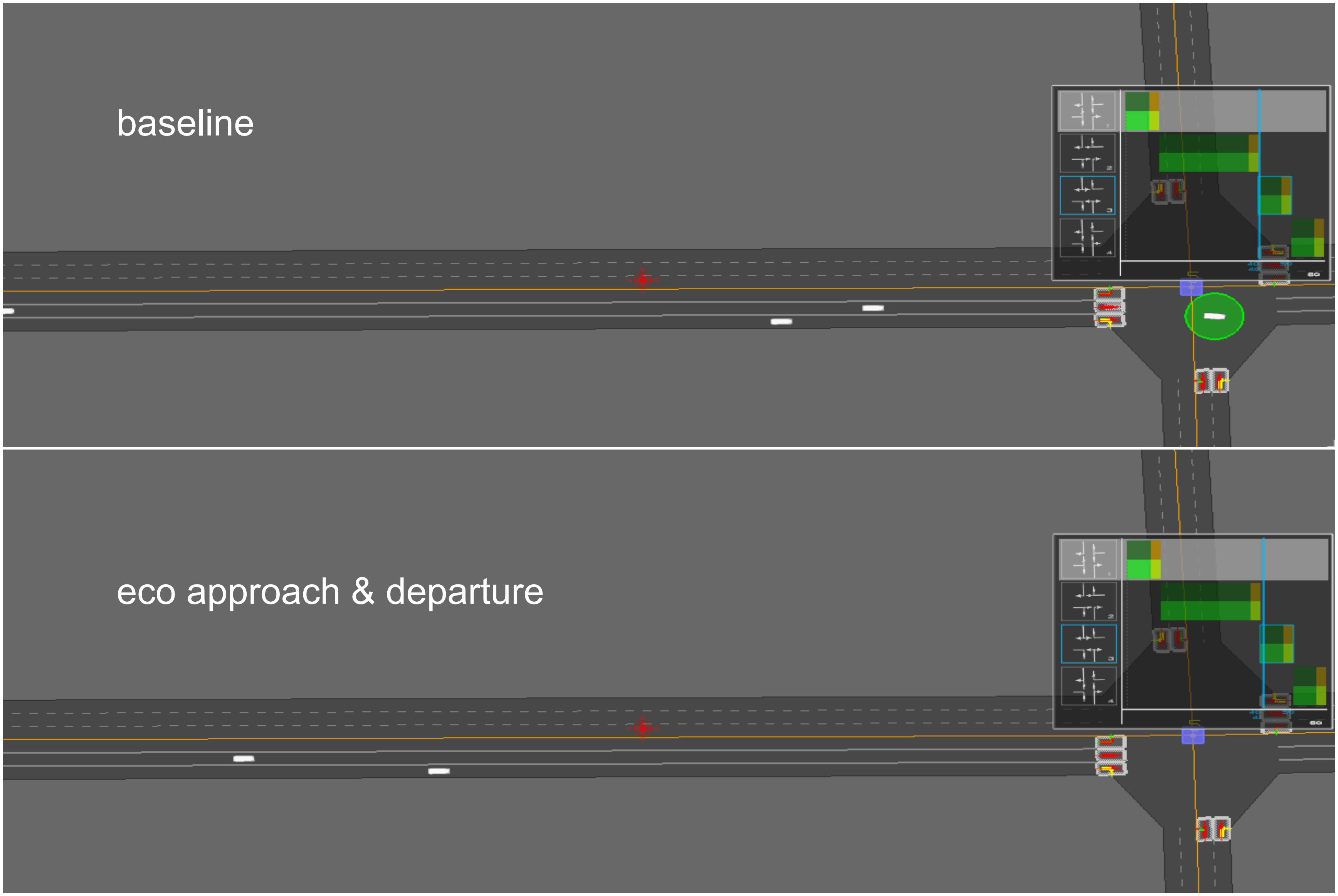
Scenario 4: Slow Down to pass through Intersection





- The vehicle needs to slow down to pass through the intersection on a green phase
- Energy savings result from the vehicle avoiding stopping and idling at the intersection

Simulation Modeling…



Major Research Efforts in EAD:

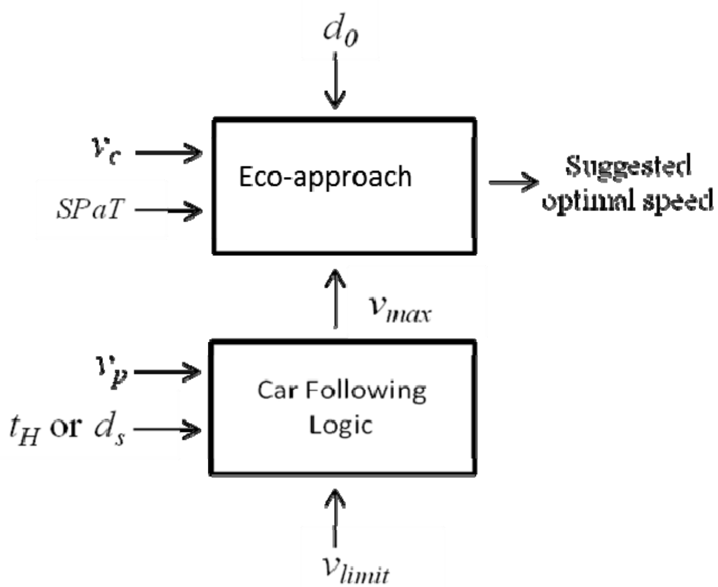
- FHWA Exploratory Advanced Research Program (EAR) in Advanced Traffic Signalization (2012 – present)
  - Phase 1: simulation and fixed time signal trials with BMW
  - Phase 2: simulation and actuated signal trials
- USDOT University Transportation Research Program supported several similar efforts
- USDOT AERIS: Applications for the Environment: Real-Time Information Synthesis
  - Phase 1: demonstration at TFHRC
  - Phase 2: extensive simulation modeling in traffic, sensitivity analyses
- FHWA GlidePath Project: applying partial automation
- Europe: GLOSA (Green Light Optimal Speed Advisory)
  - Compass4D

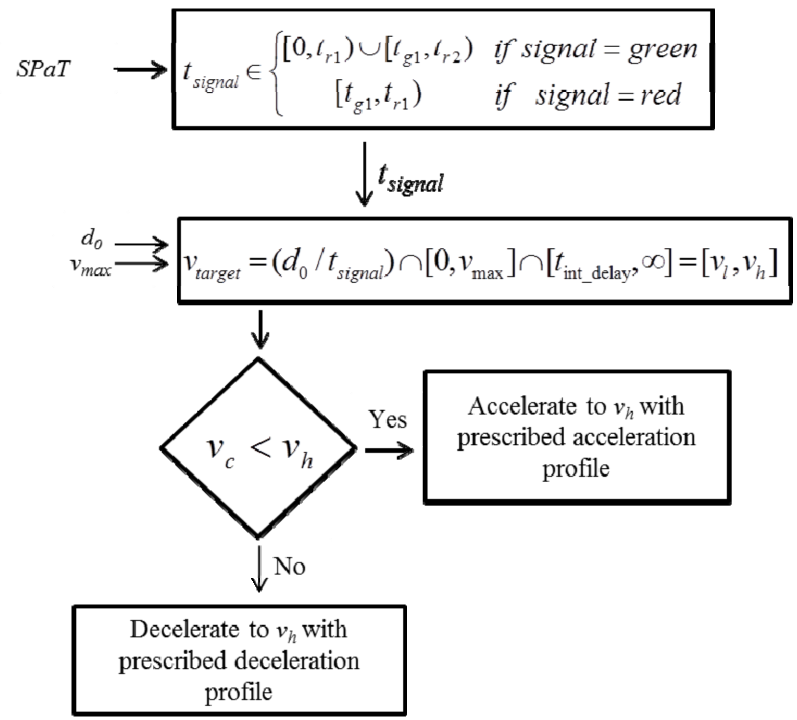
Variations of Analysis:

- Signal timing scheme matters: fixed time signals, actuated signals, coordinated signals
- Single intersection analysis and corridor-level analysis
- Congestion level: how does effectiveness change with amount of surrounding traffic
- Single-vehicle benefits and total link-level benefits
- Level of Automation: driver vehicle interface or some degree of automation
- Field Studies: typically limited to a few instrumented ingle vehicles, constrained infrastructure
- Simulation Modeling: multiple vehicles, examining the sensitivity of other variables

Velocity Planning Algorithm

- **Target velocity is set to get through the green phase of the next signal (time-distance calculation)**
- **Initial velocity may be above or below target velocity**

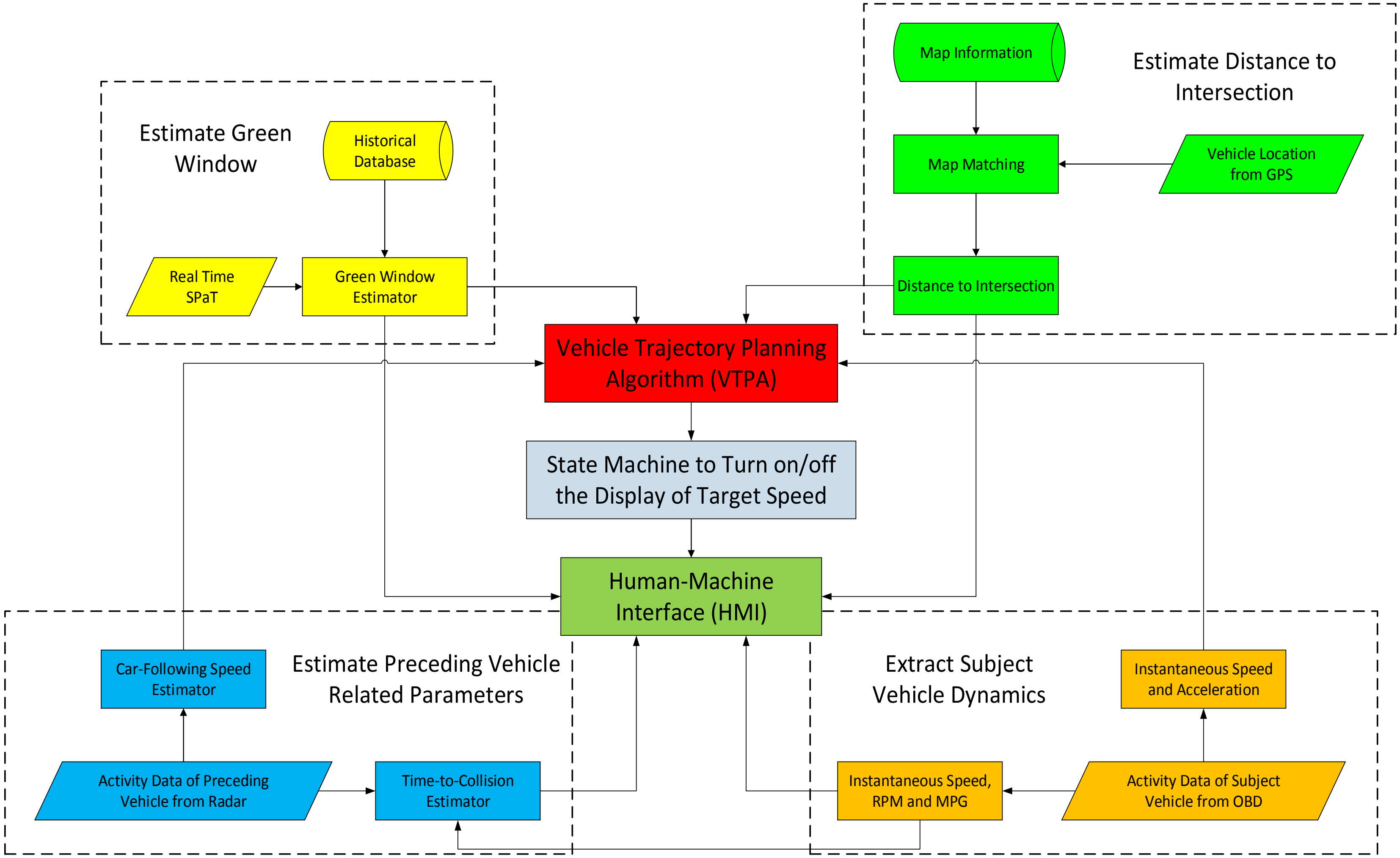




v_c = the current vehicle velocity
v_p = the velocity of the preceding vehicle
v_{limit} = local speed limit
t_H = safe headway time

Reference 1: M. Barth, S. Mandava, K. Boriboonsomsin, and H. Xia “Dynamic ECO-Driving for Arterial Corridors”, *Proceedings of the IEEE Forum of Integrated Sustainable Transportation*, Vienna Austria, 6/2011, 7 pp.
Reference 2: H. Xia, K. Boriboonsomsin and M. Barth, “Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits”, Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 17(1), 2013, pp. 31 – 41

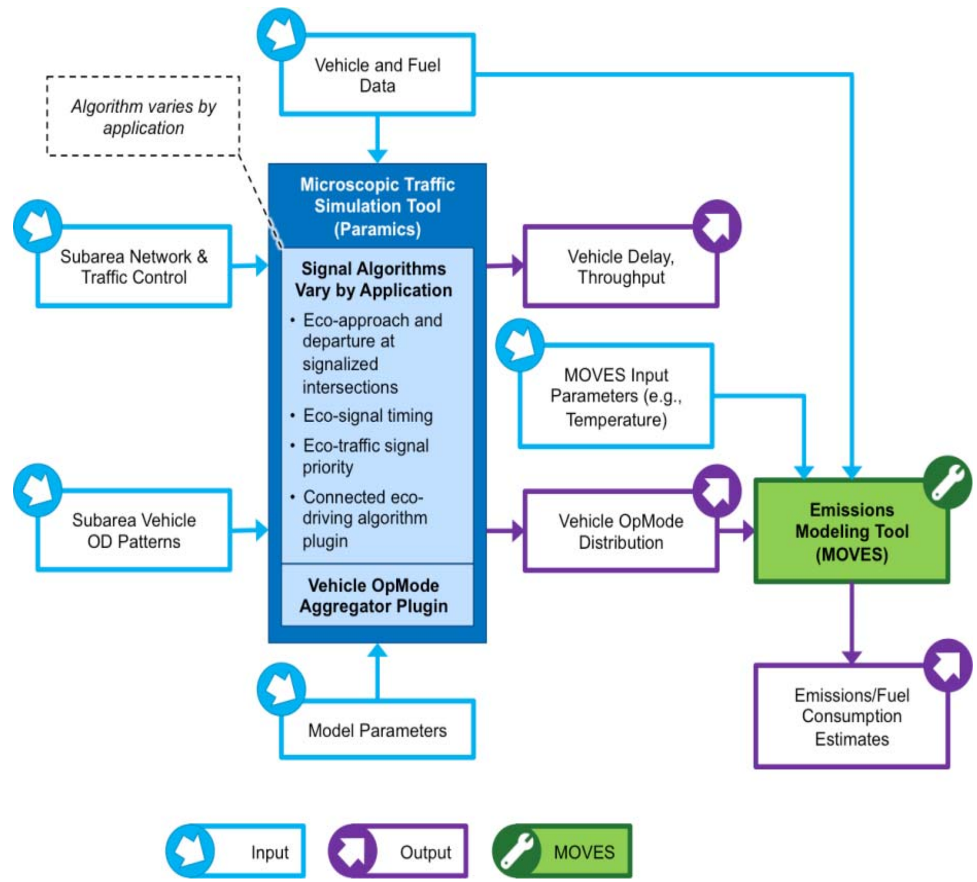
EAD Algorithm for Actuated Signal



From: P. Hao, G. Wu, K. Boriboonsomsin, and M. Barth, "Developing a Framework of Eco-Approach and Departure Application for Actuated Signal Control", Proceedings of the IEEE 2015 Intelligent Vehicle Symposium, Seoul Korea, June 2015.

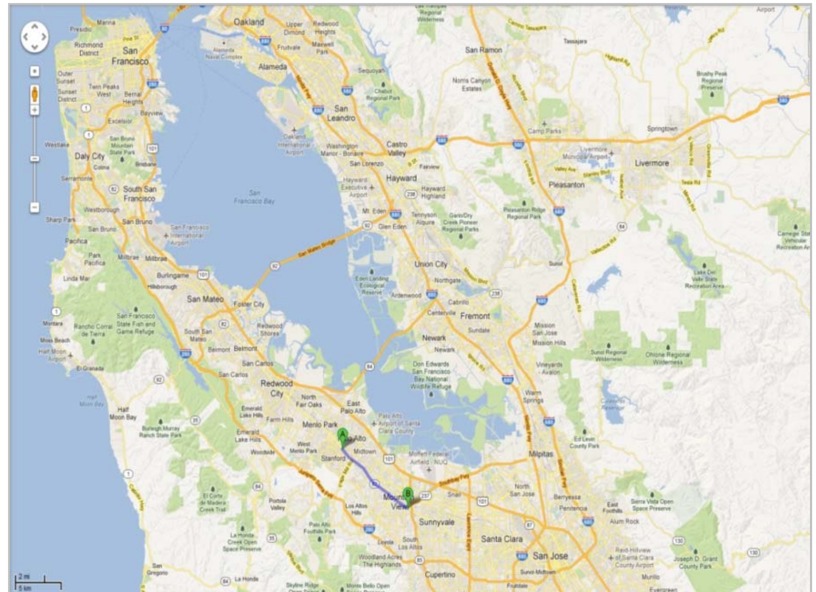
AERIS Modeling Overview

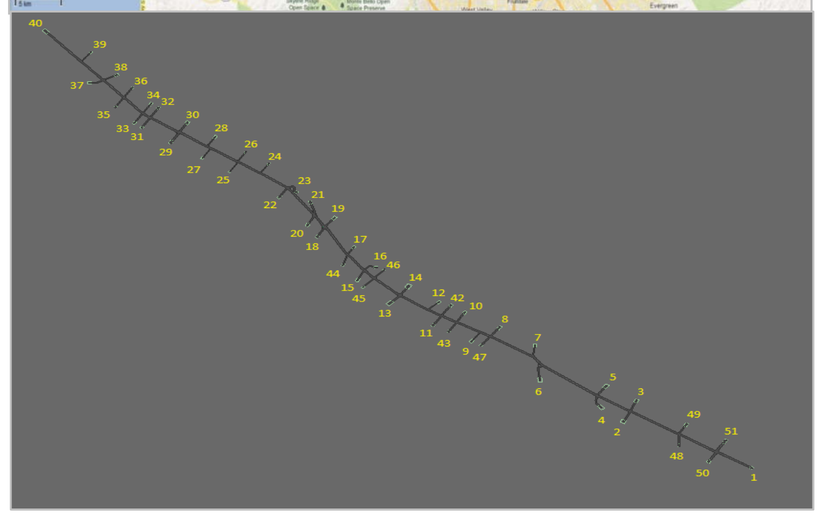
- A traffic simulation model (e.g., Paramics) was combined with an emissions model (e.g., EPA's MOVES model) to estimate the potential environmental benefits
- Application algorithms were developed by the AERIS team and implemented as new software components in the traffic simulation models
- Modeling results indicate a possible outcome – results may vary depending on the baseline conditions, geographic characteristics of the corridor, etc.



AERIS Modeling Network

- **El Camino Real Network**
  - Signalized, urban arterial (27 intersections) in northern California
  - 6.5 mile segment between Churchill Avenue in Palo Alto and Grant Road in Mountain View
  - For the majority of the corridor, there are three lanes in each direction
  - Intersection spacing varies between 650 feet to 1,600 feet
  - 40 mph speed limit
  - Vehicle demands and OD patterns were calibrated for a typical weekday in summer 2005 (high volumes on the mainline)
  - Vehicle mix (98.8% light vehicles; 1.2% heavy vehicles)





Eco-Approach and Departure at Signalized Intersections Application: Modeling Results

- **Summary of Preliminary Modeling Results**
  - **10-15%** fuel reduction benefit for an equipped vehicle;
  - **5-10%** fuel reduction benefits for traffic along an uncoordinated corridor
  - Up to 13% fuel reduction benefits for a coordinated corridor
    - 8% of the benefit is attributable to signal coordination
    - 5% attributable to the application
- **Key Findings and Takeaways**
  - The application is less effective with increased congestion
  - Close spacing of intersections resulted in spillback at intersections. As a result, fuel reduction benefits were decreased somewhat dramatically
  - Preliminary analysis indicates significant improvements with partial automation
  - Results showed that non-equipped vehicles also receive a benefit – a vehicle can only travel as fast as the car in front of it
- **Opportunities for Additional Research**
  - Evaluate the benefits of enhancing the application with partial automation:

→ **GlidePath**

EAD Dimensions of Analysis

	Fixed-time Signals	Actuated Signals
Single Vehicle	Field study 2012 (FHWA EAR P1, AERIS) Simulation modeling 2012 (AERIS) GlidePath	Field studies 2014/15 (FHWA-EAR-P2 @PATH FHWA-EAR-P2 @UCR) Limited simulation modeling 2014 (FHWA-EAR-P2)
Vehicle in Traffic	~~Field study~~ Simulation modeling 2013 (AERIS sensitivity analysis)	Field studies 2014/15 (FHWA-EAR-P2 @PATH FHWA-EAR-P2 @UCR) Field study/Demo 2015 (FHWA-EAR-P2 ECR)

Vehicle Control:

Driver with DVI

⇩

longitudinal control
(GlidePath project, 2014/15)

⇩

longitudinal control with V2V

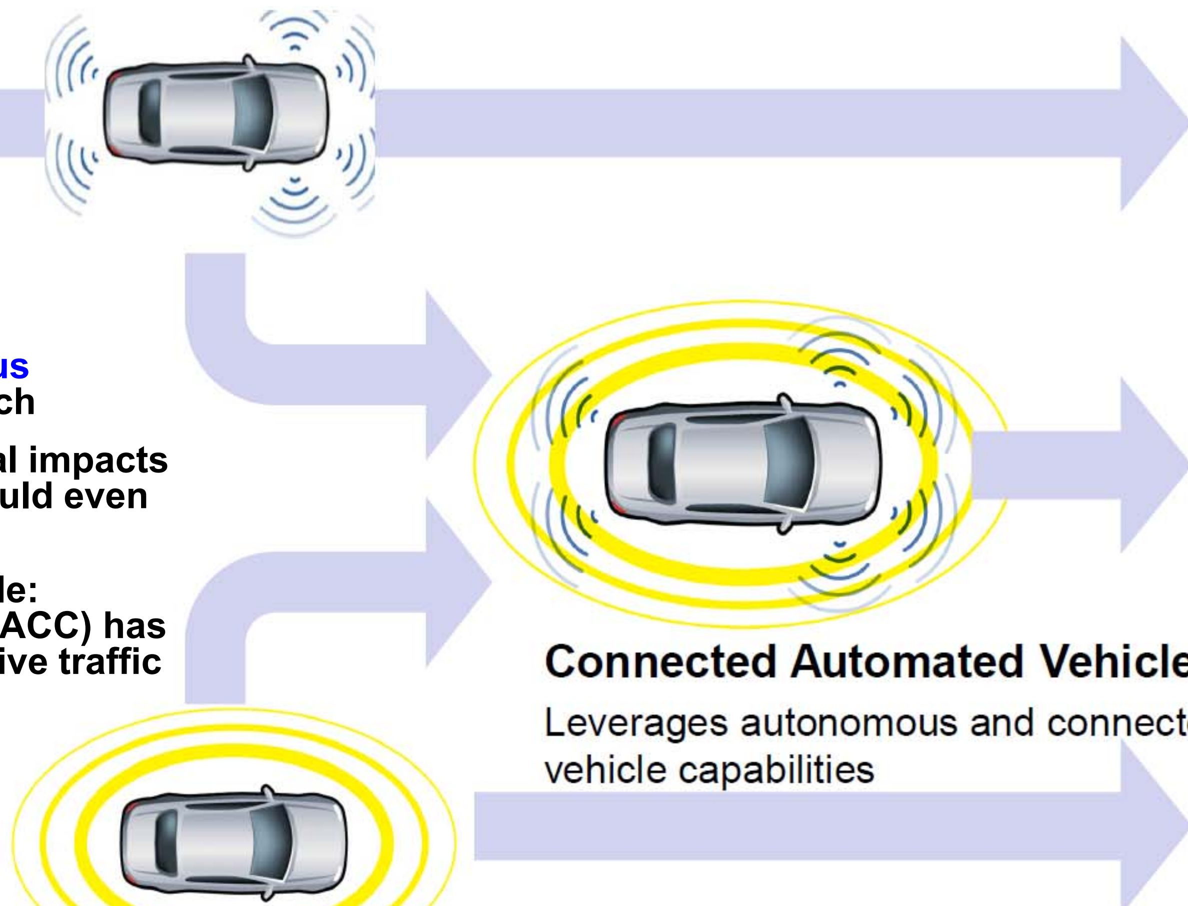
Merging of Connected Vehicles and Automation

Autonomous Vehicle

Operates in isolation from other vehicles using internal sensors

Traffic operations with autonomous vehicles will not likely change much

- **Mobility and Environmental impacts will remain the same or could even get worse**
- **Partial Automation Example: automated cruise control (ACC) has been shown to have negative traffic mobility impacts**



Connected Vehicle

Communicates with nearby vehicles and infrastructure

Traffic operations with connected automated vehicles will have a improved mobility and environmental impacts

GlidePath Prototype Application

Objectives and Period of Performance

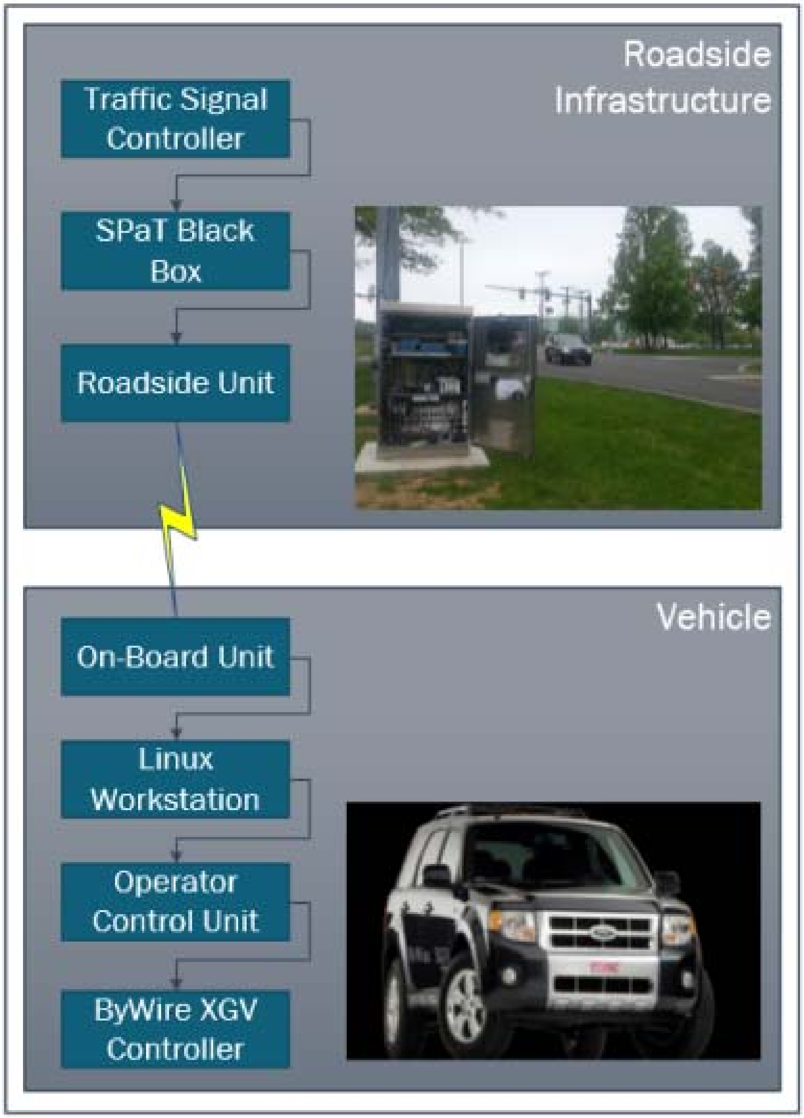
- **Project Objectives**
  - Develop a working prototype GlidePath application with automated longitudinal control for demonstration and future research;
  - Evaluate the performance of the algorithm and automated prototype (specifically, the energy savings and environmental benefits);
  - Conduct testing and demonstrations of the application at TFHRC

- **Period of Performance:**
  - May 2014 through December 2015

GlidePath Prototype Application

High-Level System Architecture

- **Component Systems**
  - **Roadside Infrastructure**
    - Signal Controller
    - SPaT Black Box
    - DSRC RSU
  - **Automated Vehicle**
    - Existing Capabilities
    - Additional Functionality
  - **Algorithm**
    - Objective
    - Input
    - Output



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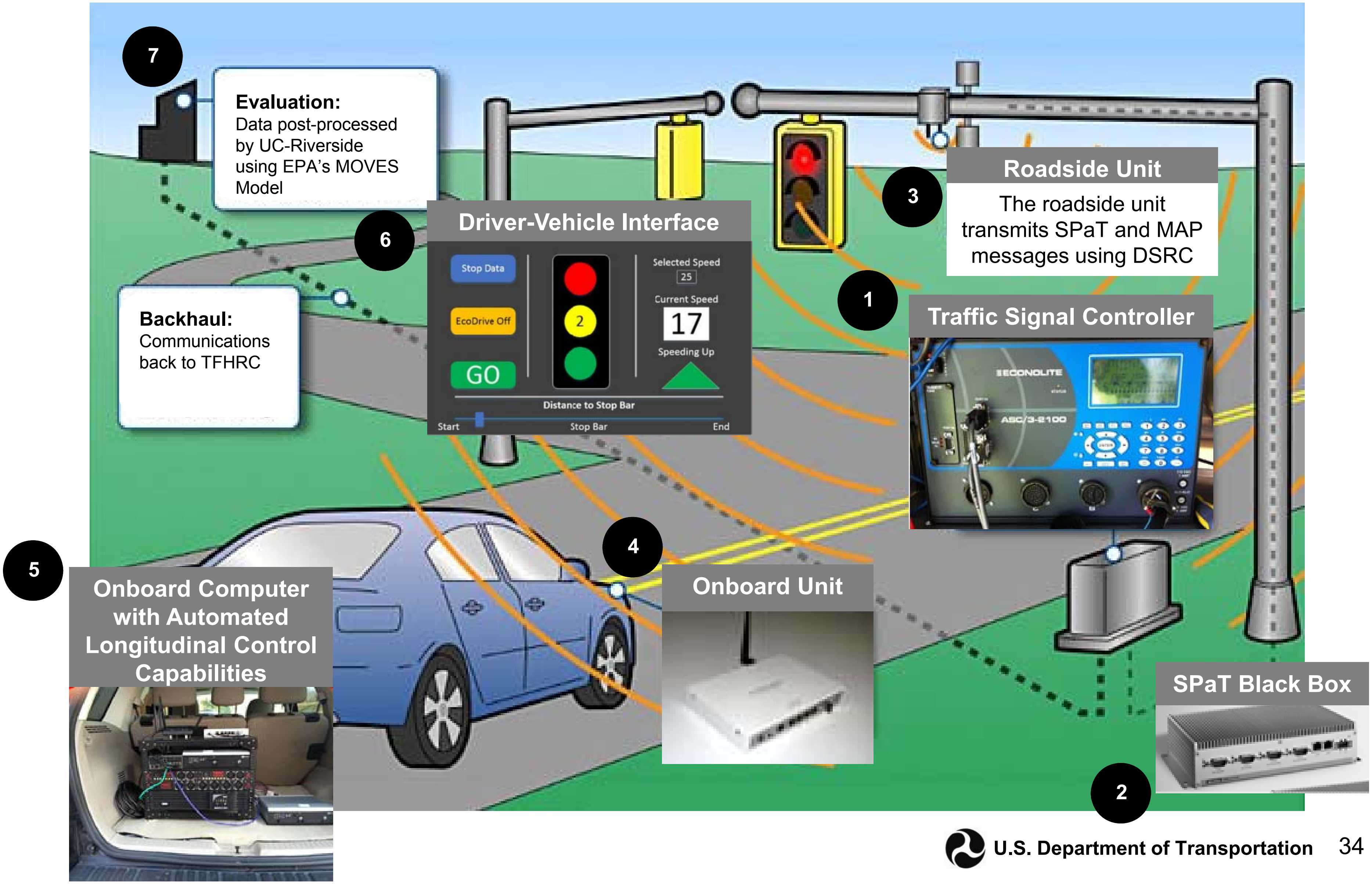
Components – Architecture



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Components – Roadside Infrastructure

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Components – Automated Vehicle

- **Ford Escape Hybrid developed by TORC with ByWire XGV System**
  - Existing Capabilities
    - Full-Range Longitudinal Speed Control
    - Emergency Stop and Manual Override
  - Additional Functionality
    - Computing Platform with EAD Algorithm
    - DSRC OBU
    - High-Accuracy Positioning Solution
    - Driver Indicators/ Information Display
    - User-Activated System Resume
    - Data Logging

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Components – Vehicle Instrumentation

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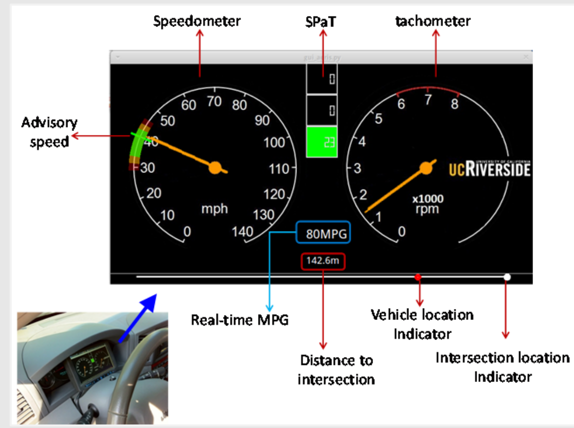
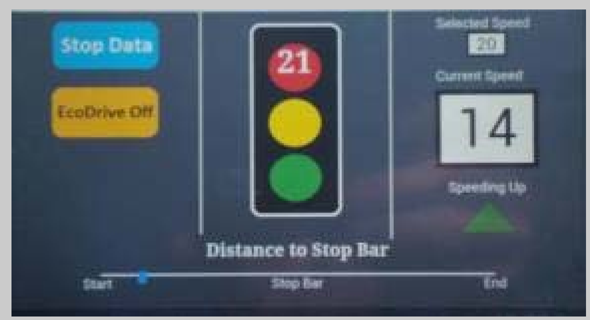
Experimental Approach

Driving Future Highways — SAXTON LABORATORY

The field experimentation will be organized into three stages

Stage I: Manual-uninformed (novice) Driver	Manual
Stage II: Manual-DVI Driver (2012 AERIS experiment)	
Stage III: Automated Driver	

Example Video (scenario 4)

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Experimental Design

Expected Scenario Outcome for Test Runs

Current Phase	Red						Y	Green				
v \ t	0	5	10	15	20	25	30	35	40	45	50	55
20 mph	Scenario 1					Scenario 2		Scenario 4				S3
25 mph	S4	Scenario 1						Scenario 3			Scenario 4	
30 mph (trials)	Scenario 4		Scenario 1						Scenario 3			S4

Scenarios will be run in each of the three (3) stages:

- Stage I: Manual-uninformed driver
- Stage II: Manual-DVI driver
- Stage III: Automated driver

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Preliminary Results

Table 1. Example driver's fuel consumption (g/mi) for different entry time (speed 20 mph)

Phase	Green						Red						Avg.
Time (s)	2	7	12	17	22	27	2	7	12	17	22	27	
Stage 2 vs. Stage 1 (DVI vs. Uninformed Driver)	-11.80	-11.75	7.59	5.20	7.56	12.05	25.08	37.80	-18.34	21.71	-0.55	13.53	**7.343**
Stage 3 vs. Stage 1 (Automated vs. Uninformed Driver)	4.67	7.55	35.25	20.94	20.28	31.71	32.65	47.91	-3.95	26.48	20.05	22.89	**22.20**
Stage 3 vs. Stage 2 (Automated vs. DVI)	14.73	17.27	29.93	16.60	13.76	22.36	10.11	16.25	12.16	6.10	20.48	10.83	**15.88**

Scenario 1   Scenario 2   Scenario 3   Scenario 4

- Four different drivers were part of the experimentation, each conducting Stage I, II, and III at two different speeds (20 mph and 25 mph)
- General Results thus far:
  - DVI (Stage II) improved fuel economy over uninformed driving (Stage I) by only **5%** on average, with a wide range of responses (**18%** standard deviation)
  - Some drivers with the DVI (Stage II) performed worse than uninformed driving (Stage I)
  - Automation (Stage III) improved fuel economy over uninformed driving (Stage I) by **20%** on average, within a narrow range of responses (**6%** standard deviation)

GlidePath Prototype Application

Lessons Learned

- Minimizing controller lag on the vehicle is important
- The Eco-Approach and Departure at Signalized Intersections algorithm and vehicle control perform well with 2-meter positioning accuracy; however precise positioning is more important near the intersection stop bar
- “Creep” towards the intersection can feel very un-natural (under scenario 4)

AERIS OPERATIONAL SCENARIOS & APPLICATIONS

ECO-SIGNAL OPERATIONS

- **Eco-Approach and Departure at Signalized Intersections** *(similar to SPaT)*
- **Eco-Traffic Signal Timing** *(similar to adaptive traffic signal systems)*
- **Eco-Traffic Signal Priority** *(similar to traffic signal priority)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Wireless Inductive/Resonance Charging**

ECO-LANES

- **Eco-Lanes Management** ***(similar to HOV Lanes)***
- **Eco-Speed Harmonization** ***(similar to variable speed limits)***
- **Eco-Cooperative Adaptive Cruise Control** *(similar to adaptive cruise control)*
- **Eco-Ramp Metering** *(similar to ramp metering)*
- **Connected Eco-Driving** *(similar to eco-driving)*
- **Wireless Inductive/Resonance Charging**
- **Eco-Traveler Information Applications** *(similar to ATIS)*

LOW EMISSIONS ZONES

- **Low Emissions Zone Management** *(similar to Low Emissions Zones)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Eco-Traveler Information Applications** *(similar to ATIS)*

ECO-TRAVELER INFORMATION

- **AFV Charging/Fueling Information** *(similar to navigation systems providing information on gas station locations)*
- **Eco-Smart Parking** *(similar to parking applications)*
- **Dynamic Eco-Routing** *(similar to navigation systems)*
- **Dynamic Eco-Transit Routing** *(similar to AVL routing)*
- **Dynamic Eco-Freight Routing** *(similar to AVL routing)*
- **Multi-Modal Traveler Information** *(similar to ATIS)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*

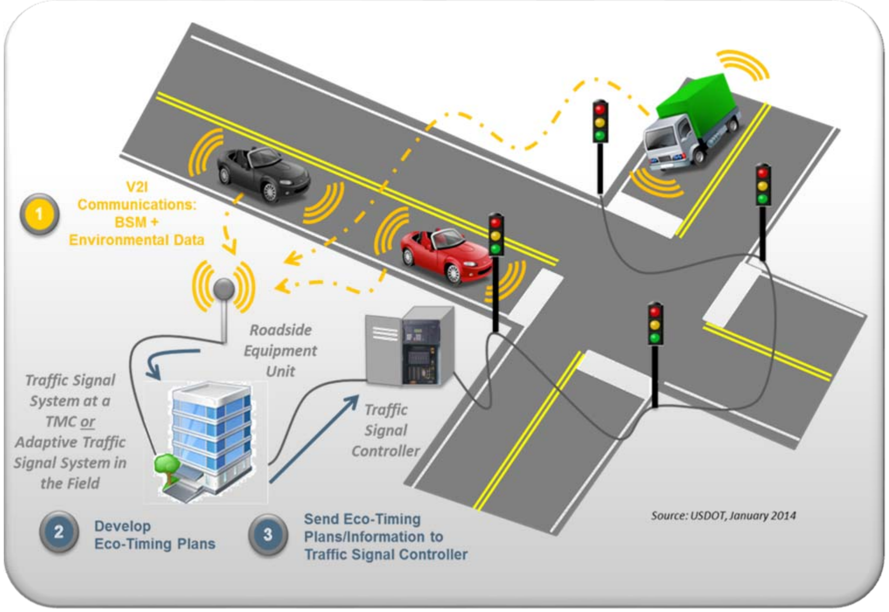
ECO-INTEGRATED CORRIDOR MANAGEMENT

- **Eco-ICM Decision Support System** *(similar to ICM)*
- **Eco-Signal Operations Applications**
- **Eco-Lanes Applications**
- **Low Emissions Zone s Applications**
- **Eco-Traveler Information Applications**
- **Incident Management Applications**

Eco-Traffic Signal Timing Application

Application Overview

- Similar to current traffic signal systems; however the application's objective is to optimize the performance of traffic signals for the environment
- Collects data from vehicles, such as vehicle location, speed, vehicle type, and emissions data using connected vehicle technologies

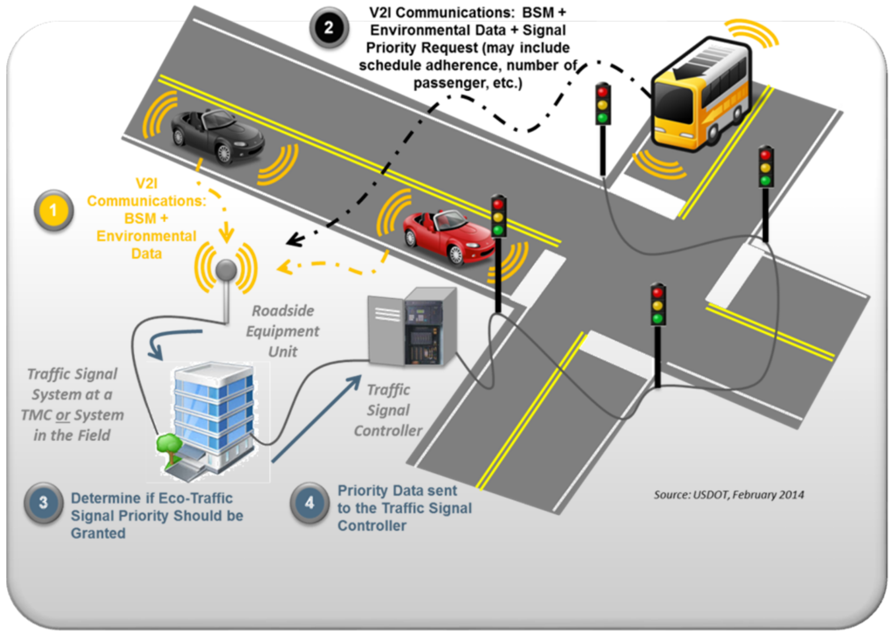


- Processes these data to develop signal timing strategies focused on reducing fuel consumption and overall emissions at the intersection, along a corridor, or for a region
- Evaluates traffic and environmental parameters at each intersection in real-time and adapts the timing plans accordingly

- **5% Energy Benefit**

Eco-Traffic Signal Priority Application

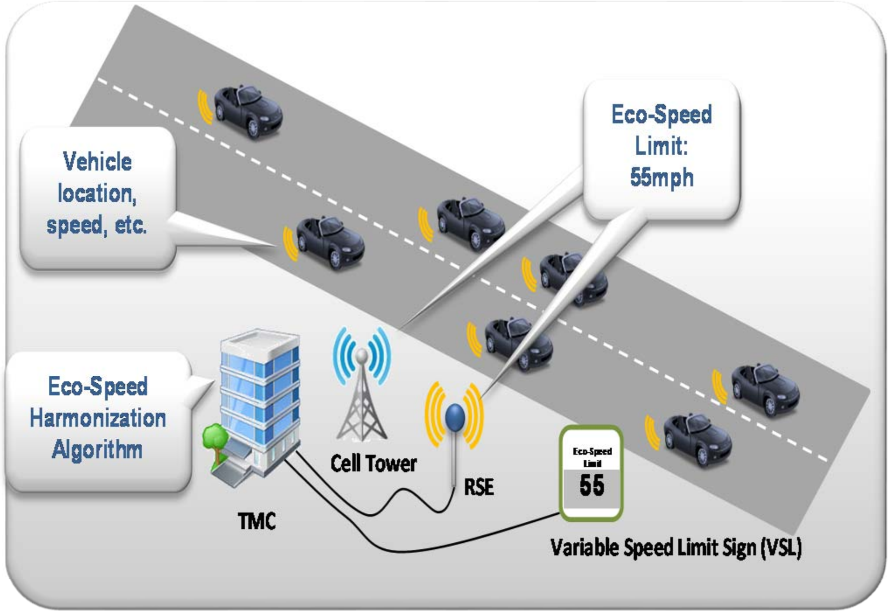
Application Overview



- Allows either transit or freight vehicles approaching a signalized intersection to request signal priority
- Considers the vehicle's location, speed, vehicle type (e.g., alternative fuel vehicles), and associated emissions to determine whether priority should be granted
- Information collected from vehicles approaching the intersection, such as a transit vehicle's adherence to its schedule, the number of passengers on the transit vehicle, or weight of a truck may also be considered in granting priority
- If priority is granted, the traffic signal would hold the green on the approach until the transit or freight vehicle clears the intersection
- **~4% Energy Benefit for freight; ~6% for all vehicles**

Eco-Speed Harmonization Application

Application Overview



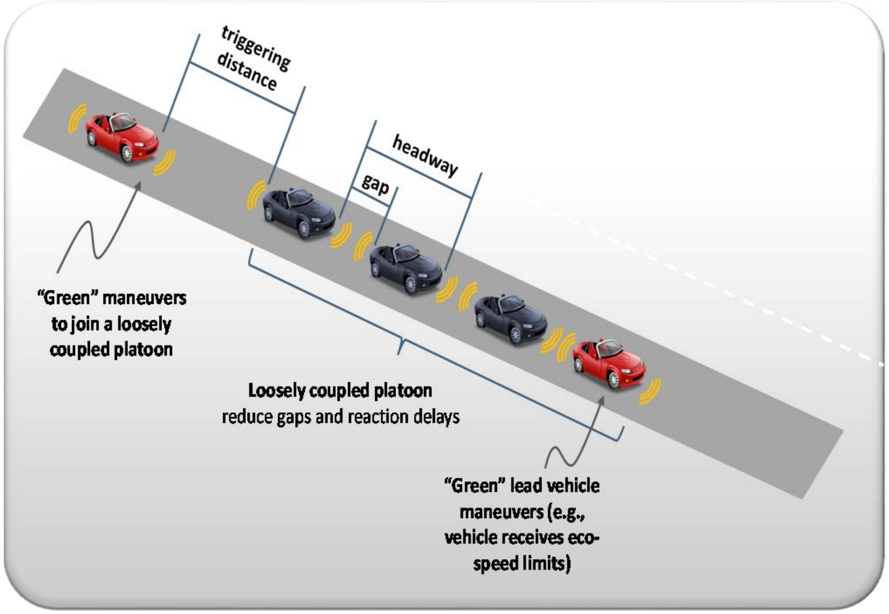
- Collects traffic information and pollutant information using connected vehicle-to-infrastructure (V2I) communications
- The application assists in maintaining flow, reducing unnecessary stops and starts, and maintaining consistent speeds near bottleneck and other disturbance areas
- Receives V2I messages, the application performs calculations to determine the optimal speed for the segment of freeway where the bottleneck, lane drop, or disturbance is occurring
- The optimal “eco-speed” is broadcasted by V2I messages from roadside RSE equipment to all connected vehicles along the roadway

- **~4.5% Energy Benefit**

Eco-Cooperative Adaptive Cruise Control (CACC) Application

Application Overview

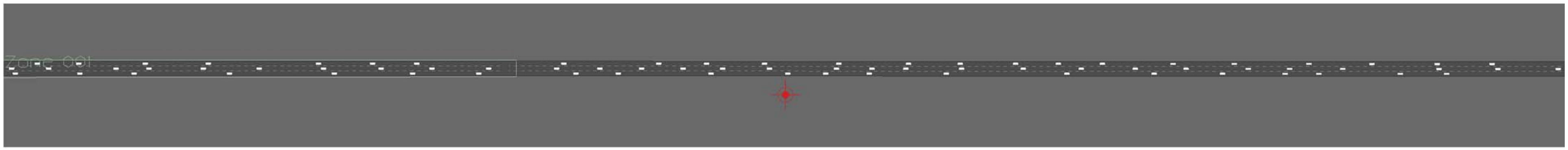
- Eco-CACC includes longitudinal automated vehicle control while considering eco-driving strategies.
- Connected vehicle technologies can be used to collect the vehicle's speed, acceleration, and location and feed these data into the vehicle's ACC.



- Receives V2V messages between leading and following vehicles, the application performs calculations to determine how and if a platoon can be formed to improve environmental conditions
- Provides speed and lane information of surrounding vehicles in order to efficiently and safely form or decouple platoons of vehicles

CACC Applied to a General Freeway Segment

Baseline



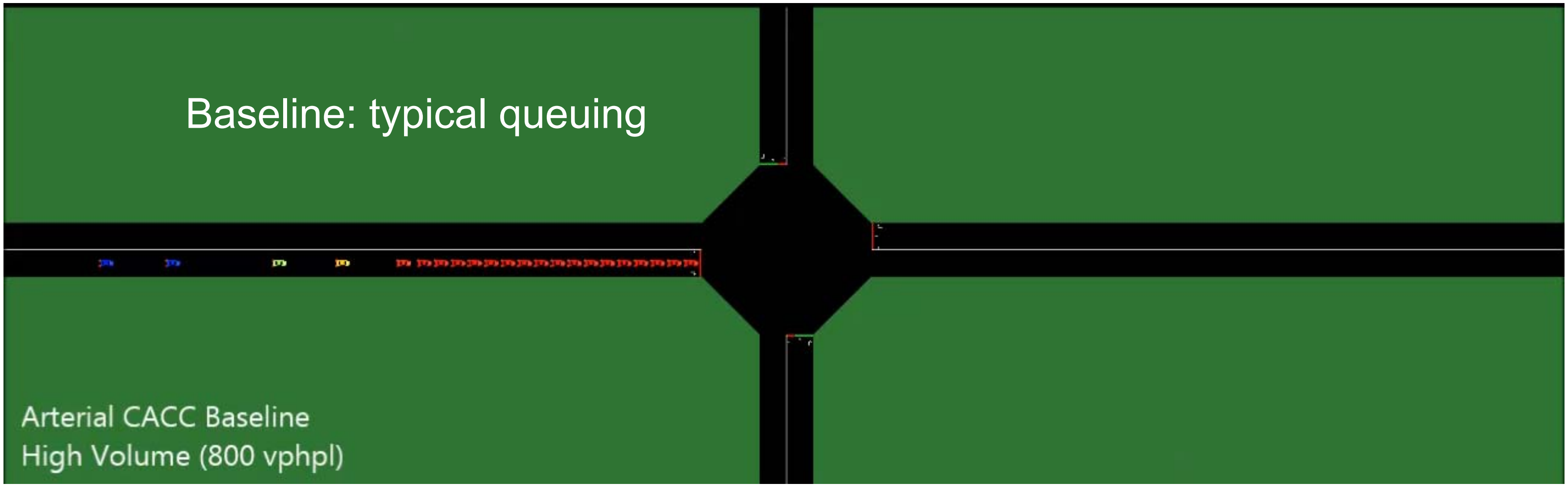
Upstream Segment with CACC Platoon Formation

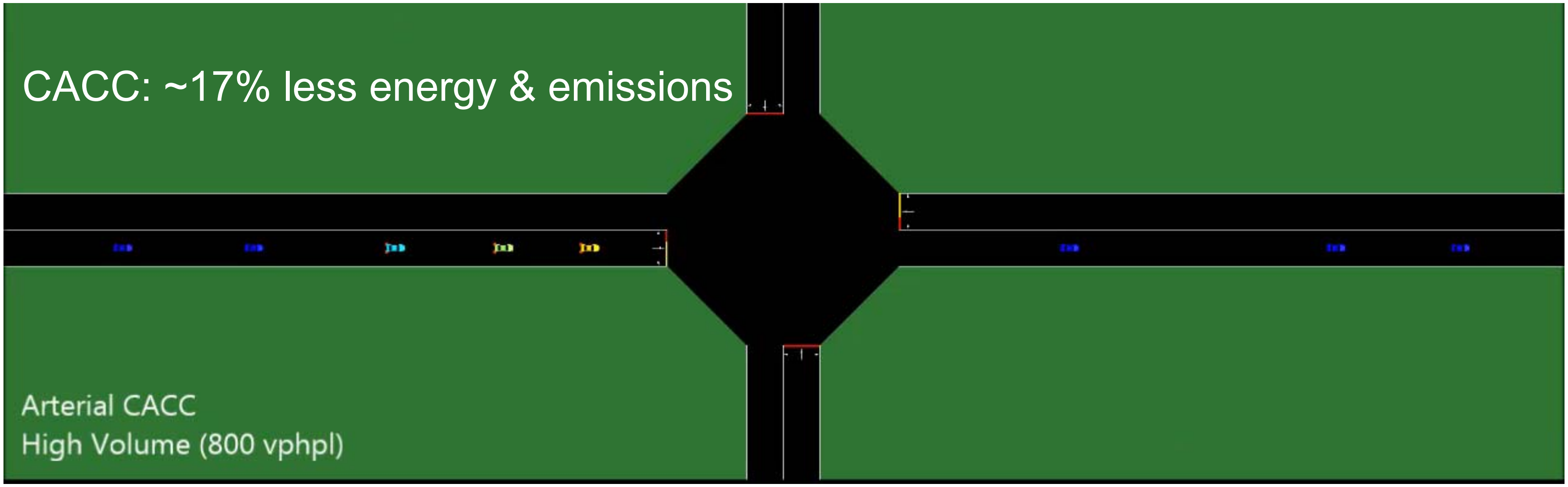
Downstream Segment with CACC Platoons

Eco-Cooperative Adaptive Cruise Control (CACC) Application: Modeling Results

- **Summary of Key Modeling Results**
  - Up to **19%** fuel savings on a real-world freeway corridor
  - Up to an additional **7%** fuel savings when using a dedicated “eco-lane” instead of general purpose lane on the freeway corridor
  - Up to **42%** travel time savings on a real-world freeway corridor
- **Key Findings and Takeaways**
  - The presence of a single dedicated “eco-lane” leads to significant increases in overall network capacity
  - Drivers may maximize their energy and mobility savings by choosing to the dedicated “eco-lane”
- **Opportunities for Additional Research**
  - Increasing the number of dedicated lanes will likely further improve results
  - Quantifying relationship between platoon headway and increased network capacity is also of interest

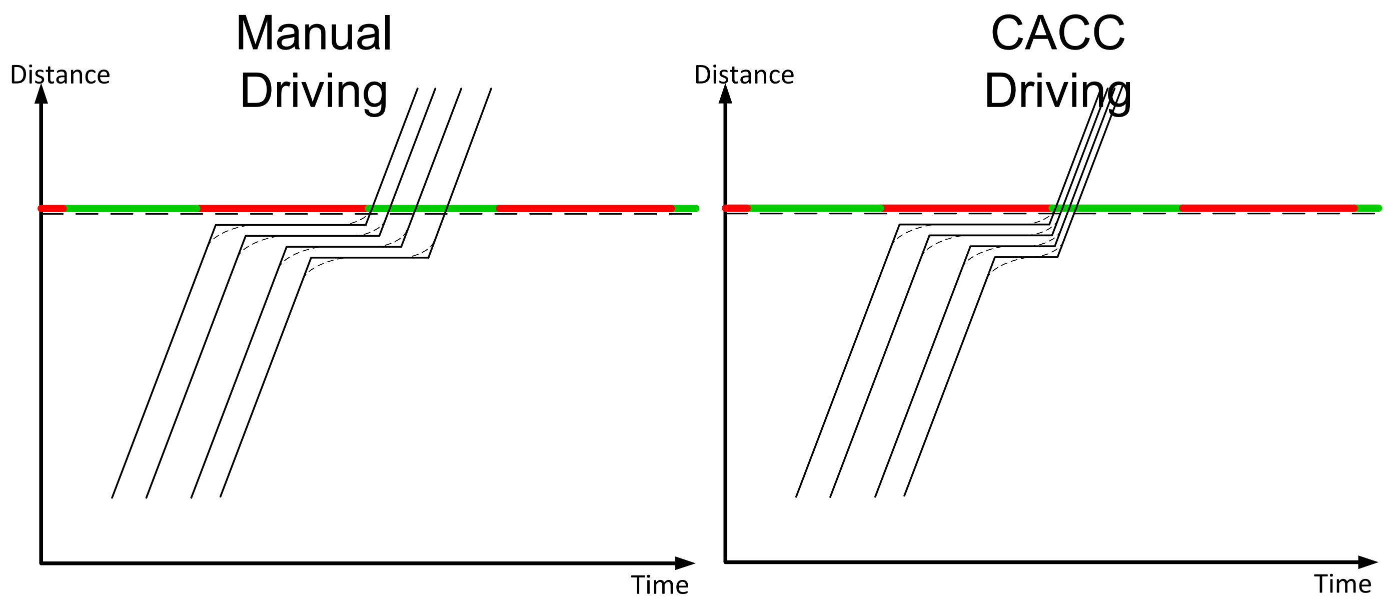
Cooperative Adaptive Cruise Control applied to Intersections





Cooperative Adaptive Cruise Control with Eco-Approach and Departure

- **For isolated intersection:**
  - **Approach: platoon-based eco-approach**
  - **Departure: platoon discharges with minimum headway**



AERIS OPERATIONAL SCENARIOS & APPLICATIONS

ECO-SIGNAL OPERATIONS

Traffic Energy Benefits

- **Eco-Approach and Departure at Signalized Intersections** *(similar to SPaT)* → **10% energy savings**
- **Eco-Traffic Signal Timing** *(similar to adaptive traffic signal systems)* → **5% energy savings**
- **Eco-Traffic Signal Priority** *(similar to traffic signal priority)* → **6% energy savings**
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Wireless Inductive/Resonance Charging**

ECO-LANES

- **Eco-Lanes Management** ***(similar to HOV Lanes)***
- **Eco-Speed Harmonization** ***(similar to variable speed limits)*** → **4.5% energy savings**
- **Eco-Cooperative Adaptive Cruise Control** *(similar to adaptive cruise control)* → **19% energy savings**
- **Eco-Ramp Metering** *(similar to ramp metering)*
- **Connected Eco-Driving** *(similar to eco-driving)*
- **Wireless Inductive/Resonance Charging**
- **Eco-Traveler Information Applications** *(similar to ATIS)*

LOW EMISSIONS ZONES

- **Low Emissions Zone Management** *(similar to Low Emissions Zones)*
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- **Eco-Traveler Information Applications** *(similar to ATIS)*

Stages of Connected and Automated Vehicle Applications

Phase 1:

- **Deploy DSRC radios in cars for safety, take advantage with compatible mobility and environmental applications (homogenous multi-agent systems, decentralized control)**

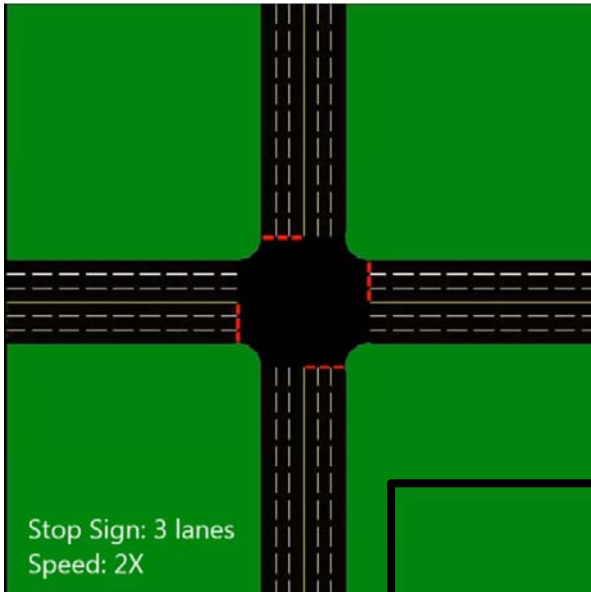
Phase 2:

- **Develop specifically designed mobility and environmental applications for greater benefits (heterogeneous multi-agent systems, decentralized and centralized control schemes, new message sets)**

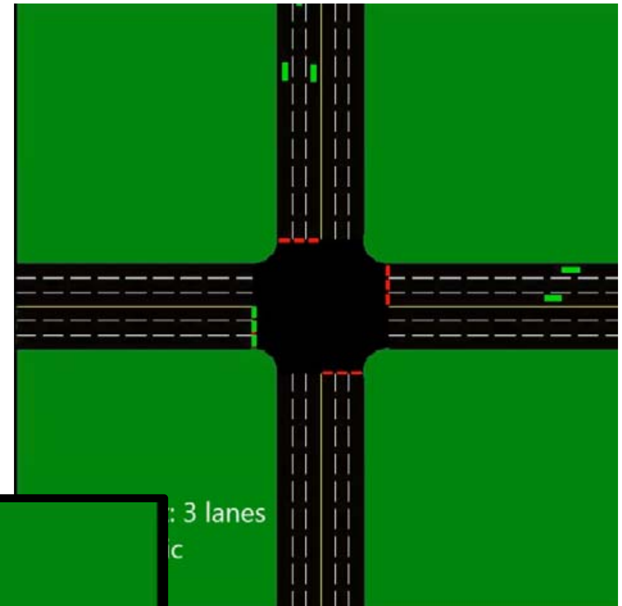
Phase 3:

- **Phase 2, but also integrate connected and automated vehicle operations and applications *with new infrastructure designs***

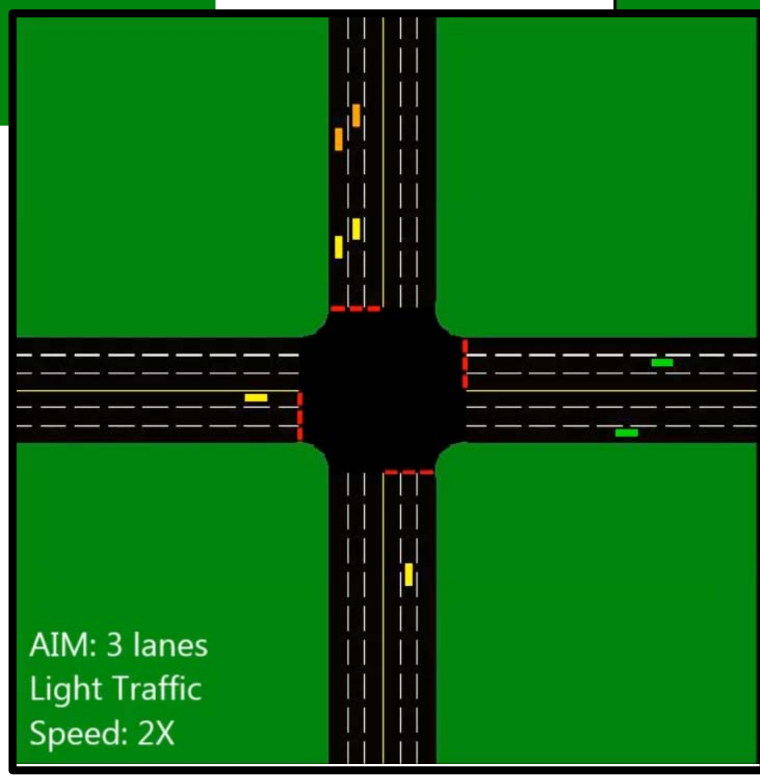
Different Intersection Management Systems



stop signs



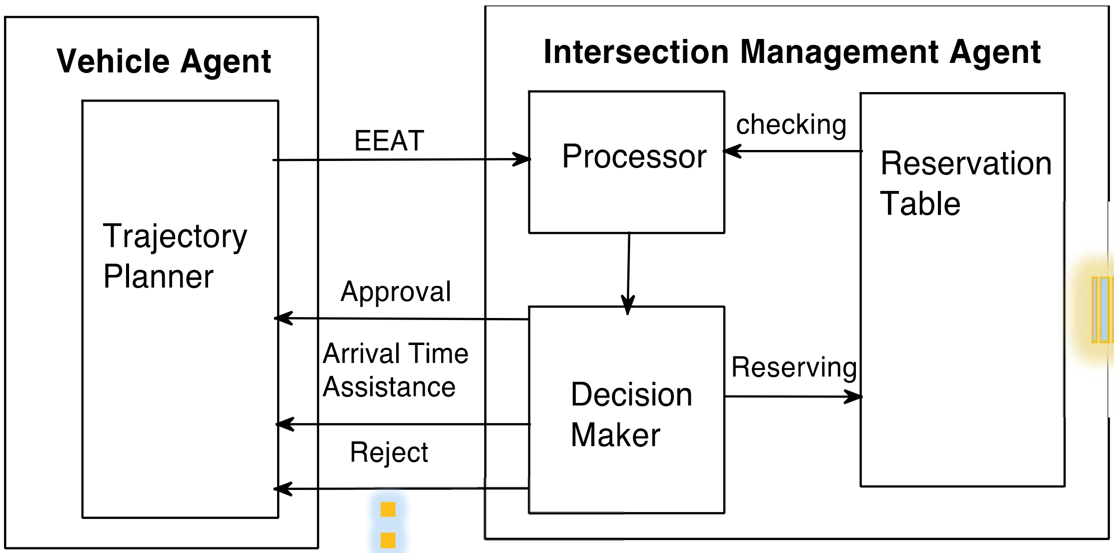
traffic light



Intersection reservation system with automated connected vehicles

Source: David Kari, UCR, 2014

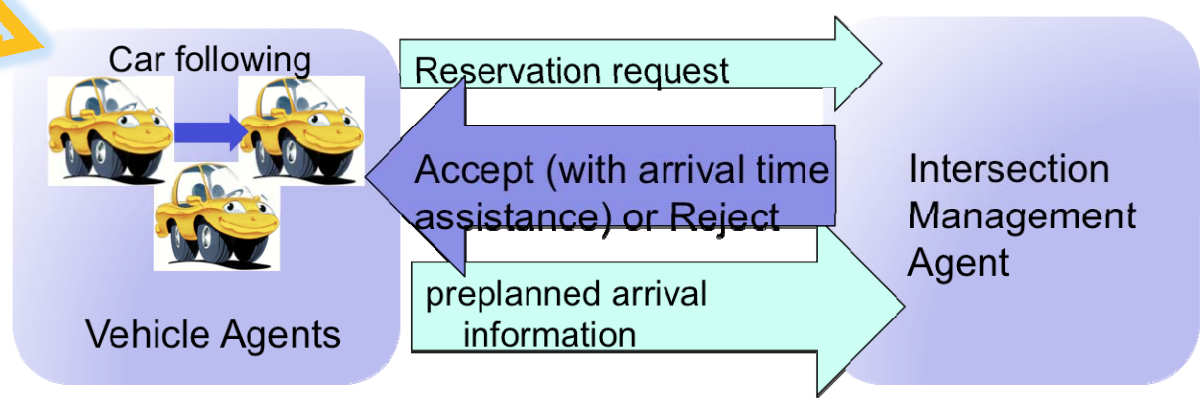
System architecture of multi-agent based dynamic reservation management



Schedule vehicle agents arrival times based on:

- Priority-based policy (level 1): vehicle's priorities
- Lane-based policy (level 2): vehicle's lane position
- FCFS (first come, first serve) policy (level 3): based on vehicle's requesting time

Interactions between Multi-agents:



Simulation Analysis and Results

- **Travel Time Improvement**
  - Two direction traffic flow : Travel time reduction ranges from 45% to 87% depending on traffic volume.
  - Travel time has 2% reduction when communication range changes from 100 meters to 300 meters.

- **Fuel consumption and Emissions Improvement**

  Two direction traffic flow compared to traditional signal control system:
  - 41% to 71% reductions for CO
  - 65% to 75% for CO_2 and fuel consumption
  - 55% to 78% for HC
  - 63% to 74% for NOx

ref: Q. Jin, G. Wu, K. Boriboonsomsin, M. Barth, "Advanced Intersection Management for Connected Vehicles Using a Multi-Agent Systems Approach", *Proceedings of the IEEE Intelligent Vehicle Symposium*, Alcalá de Henares, Spain, June 2012, 6 pp.

Round-about Merge Assist (RMA)

- **Human drivers entering a round-about typically slow down to look for hazards such as other vehicles, bicyclists, and pedestrians**
  - **Slowing down reduces intersection throughput and increases vehicle emissions/energy**

- **Automation of round-about merging via automated merging and lateral maneuvers**
  - **Improves intersection throughput**
  - **Reduces vehicle emissions/energy consumption**
  - **Is a natural stepping stone to true *continuous flow intersections***

Why Automate Round-abouts?

Round-abouts are an excellent choice for incorporating lane merging maneuvers.

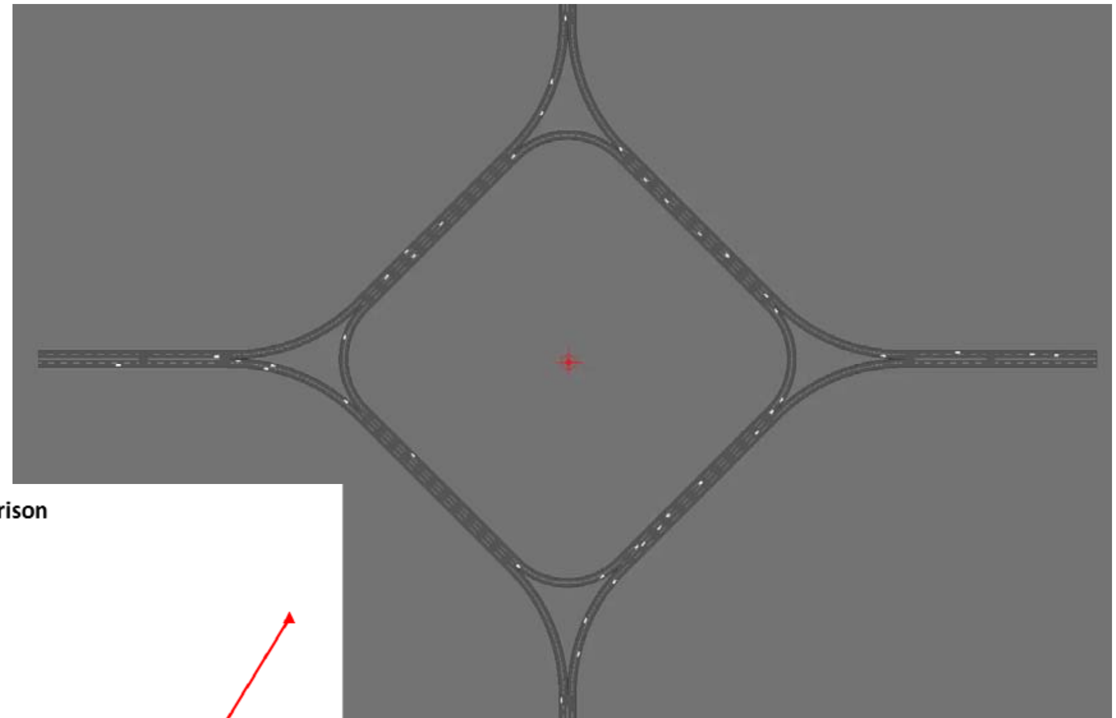
2. **Automating round-abouts is *less complex* than automating traditional 4-way intersections (Automated Merging Maneuvers vs. Autonomous Intersection Management)**

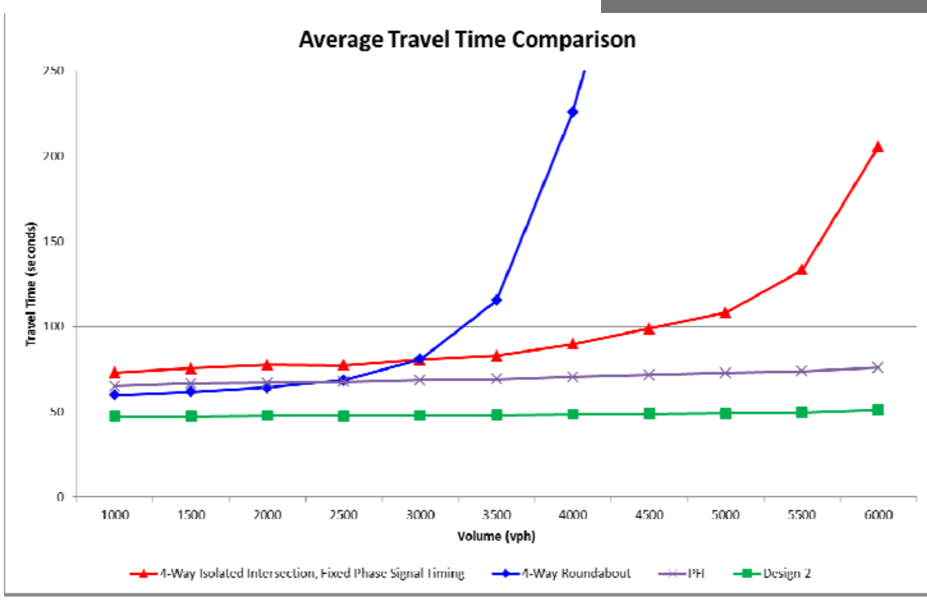
Automating traditional 4-way intersections requires reservation-based AIM

(infrastructure calculates and broadcasts specific vehicle trajectories)

Automating round-abouts requires only automating lane merge maneuvers (infrastructure support is not strictly required)

Ultimate Arterial Lane Merge Scenario is with *Continuous Flow Intersections*

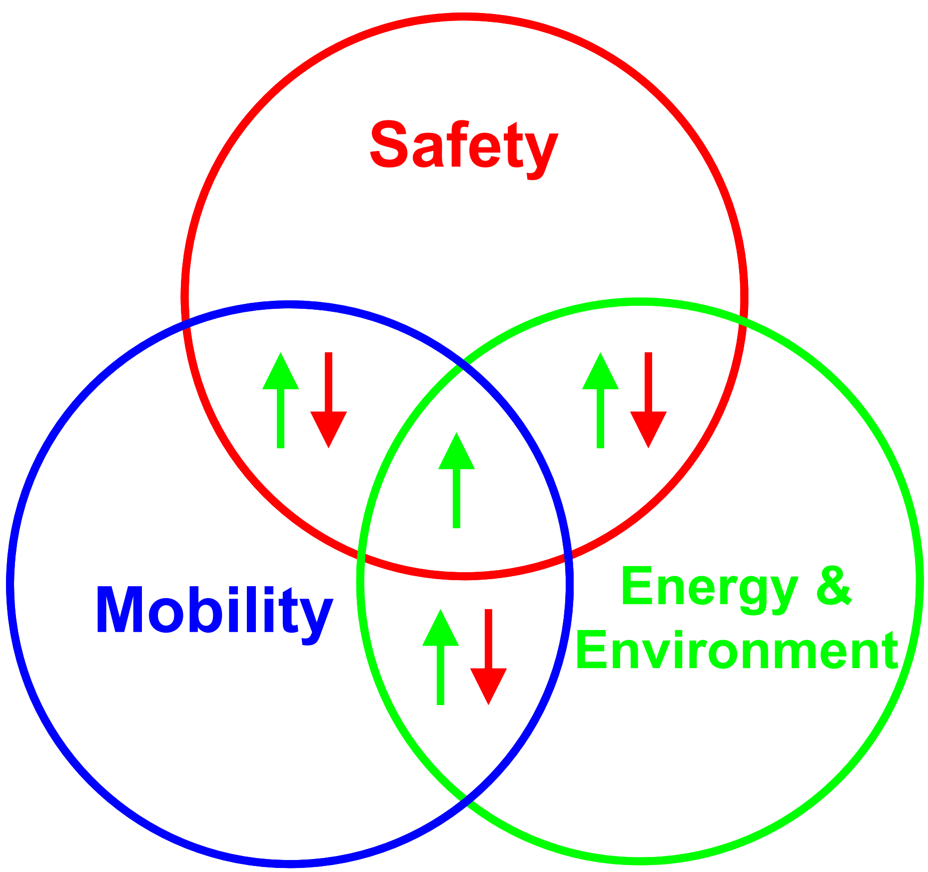




Key Take Away Points:

- Partial and full automation can provide better energy & emission results compared to human-machine interfaces, depending on design of control system
- With automation, system design trade-offs will exist between safety, mobility, and the environment (e.g., automated maneuvers)
- Connected automated vehicles will likely have greater improvements in mobility and environment compared to autonomous vehicles
- Basic Safety Messages can be used for energy and emissions estimates
- Advanced Connected and Automated Vehicle operation will have a greater benefit with changes to the infrastructure

Future Work: Synergies and Tradeoffs of Safety, Mobility, and Environment



Safety & Mobility:

- Collision avoidance
- Increased spacings

Safety & Energy:

- Electronic Brake Lights
- Conservative automated maneuvers

Mobility & Energy:

- CACC
- Higher speeds